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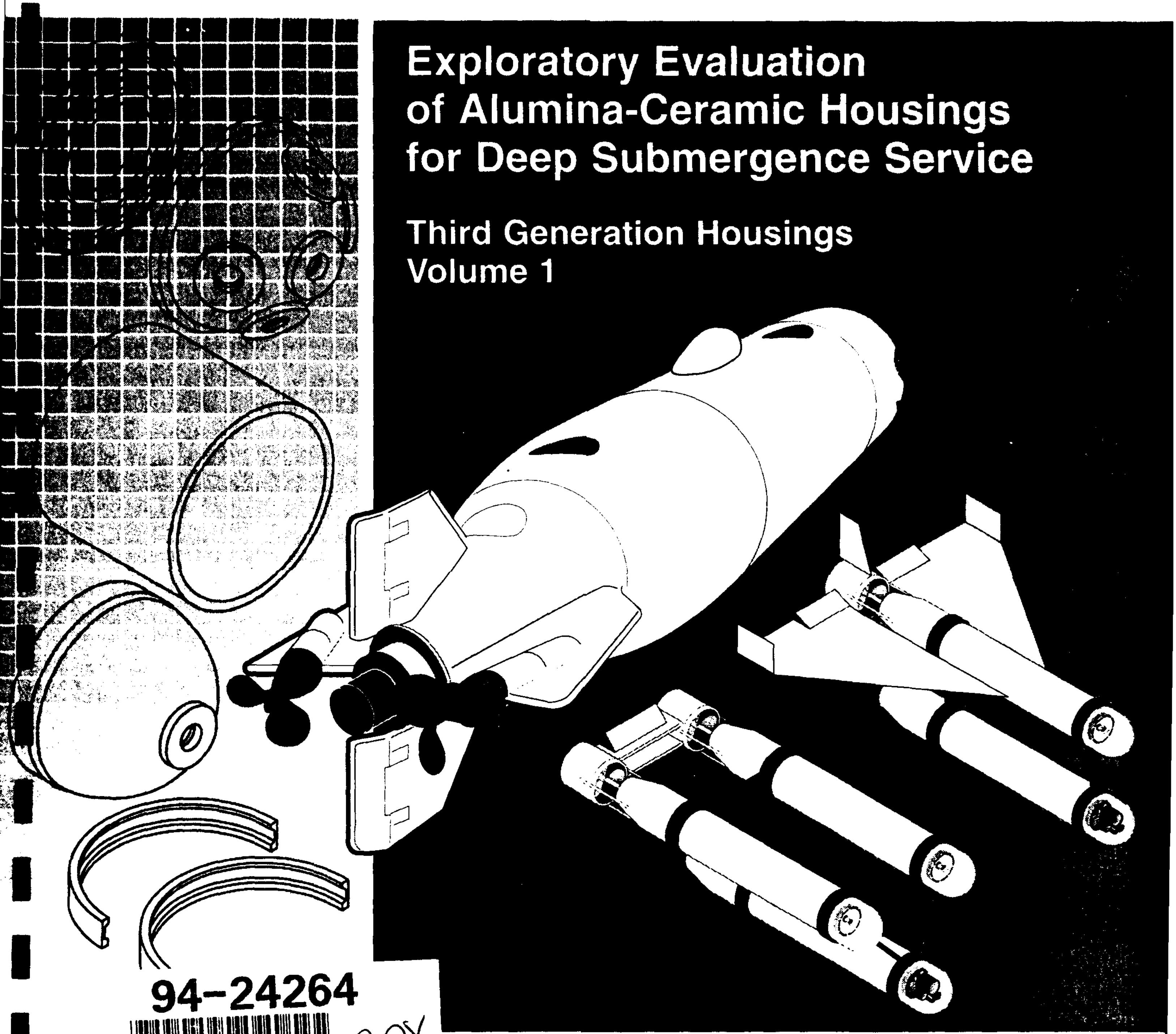
Exploratory Evaluation of Alumina-Ceramic Housings for Deep Submergence Service

Third Generation Housings
Volume 1



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J. D. Stachiw

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Third Generation Housings
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ADMINISTRATIVE INFORMATION

This work was performed by the Marine Materials Technical Staff, RDT&E Division of the Naval Command, Control and Ocean Surveillance Center, for the Naval Sea Systems Command, Washington, DC 20362.

Because the program extended over several years and covered many technical areas, publication of this report was delayed until now.

Released by
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SUMMARY

Ceramic materials have the potential of providing external pressure housings for a design depth of 20,000 feet with a weight-to-displacement (W/D) ratio $\leq$0.5, provided that the problem areas associated with the use of ceramics for this application can be successfully resolved.

Previous studies already have shown conclusively that ceramics can be successfully applied to the fabrication of monocoque and rib-stiffened cylinders capable of withstanding high external hydrostatic pressures. Because of their potential to become a cost-effective material for construction of external pressure housings, a program was initiated at Naval Ocean Systems Center (NOSC)[1] with an objective to demonstrate the feasibility of assembling entire housing assemblies from ceramic components.

To meet this objective, the following features of ceramic housing construction had to be demonstrated successfully:

a. *Ceramic hemispheres* with multiple penetrations containing bulkhead penetrators can be designed and fabricated to be stronger, but, at the same time, lighter, than titanium bulkheads of similar size.

b. *Ceramic cylinders* can be fastened to titanium, or ceramic hemispheres with a mechanical joint that allows rapid access to their interiors.

c. *Metallic ring stiffeners* can be incorporated either into the cylinders, or the joints between them, to provide the necessary intermediate radial supports to the cylinder sections joined together to form a long cylindrical housing.

d. *Nondestructive inspection* techniques can be used routinely to detect and locate internal cracks and voids of critical size capable of initiating cracks at design stress levels.

e. *Scaling up of ceramic components* in the housing does not significantly decrease their critical pressure under compressive loading, provided they have been previously nondestructively inspected and found to be free of critical-size voids.

The test and evaluation program conducted with 6- and 12-inch outside diameter (OD) housing components has successfully demonstrated engineering solutions to these problem areas. The data generated by the test program forms the basis for the design of (1) monocoque ceramic cylinders, (2) hemispherical ceramic bulkheads with multiple penetrations for electrical or hydraulic bulkhead penetrators, (3) joints between individual ceramic housing components incorporating metallic ring stiffeners, and (4) end caps for radial and axial bearing surfaces on ends of ceramics and hemispheres.

As a result of this investigation, a design was developed for protecting the ends of ceramic cylinders and hemispheres against spalling initiated by repeated pressurizations of the housing assembly. The Naval Undersea Center (NUC)[2] Mod 1 end cap design provided a fatigue life in excess of 500 pressure cycles to design pressure for the bearing surfaces on the ends of cylinders and hemispheres, as long as the axial bearing stress did not exceed –75,000 psi.

The ability to incorporate these features into the designs of ceramic housings for deep submergence service resulted in housing assemblies consisting of up to four ceramic 12-inch-diameter cylinder sections joined and supported by metallic ring stiffeners, and enclosed at both ends with ceramic hemispheres incorporating multiple bulkhead penetrators.

The housings for 9,000-psi design pressure, assembled from monocoque 94-percent alumina cylindrical sections with $t/D_0 = 0.034$ and $L/D_0 = 1.5$ when closed off by two hemispherical ceramic bulkheads with $t/D_0 = 0.017$ provide a 0.6 W/D ratio. When compared to a titanium housing of the same size with identical design pressure, the *pay-*

1. NOSC is now the Naval Command, Control and Ocean Surveillance Center (NCCOSC) RDT&E Division (NRaD).

2. NUC became NOSC, which is now NRaD.

load capability of the ceramic housing is three times larger, yet its *fabrication cost* is only about 50 percent greater.

Ultrasonic and radiographic nondestructive inspection techniques have demonstrated the ability to detect and locate voids with cross sections of $\geq$0.010 inch. Voids with cross sections of <0.050 inch did not initiate cracking, even at the –300,000 psi compressive stress level in the ceramic cylinders or hemispheres. Most of the voids detected in ceramic components had cross sections of <0.02 inch. The largest void found during the inspection of all ceramic components tested in this study was 0.05 inch in diameter.

VOLUME 1 CONTENTS

FIGURES

TABLES

VOLUME 2 CONTENTS

INTRODUCTION

Deep submergence vehicles require pressure housings for containment of electronic equipment sensitive to contact with water. In addition, if those housings are fabricated from strong, but lightweight, materials, they can provide the vehicle with positive buoyancy. This is very desirable for optimization of vehicle performance, as it eliminates bulky syntactic foam modules which otherwise must provide the necessary positive buoyancy for the vehicle.

For depths beyond 10,000 feet, even premium metallic alloys do not provide the necessary buoyancy for pressure housings, as their specific compressive strength (i.e., compressive strength divided by density) is too low for this application (table 1).* Only ceramic, glass and glass, or graphite fiber-reinforced plastic composites are sufficiently strong, and, at the same time, light enough to provide housings for an operation depth of 20,000 feet with a weight-to-displacement (W/D) ratio in the 0.4 to 0.6 range (figure 1). The intermediate depth design goal of 20,000 feet for deep submergence vehicles would allow them to explore over 98 percent of the ocean bottom (figure 2). The ultimate depth design goal is 36,161 feet, representing the deepest spot discovered to date in the world's oceans. Vehicles with pressure hulls with W/D ratios in excess of 0.6 are considered too sluggish, and/or lack the operational range required of high performance AUVs (autonomous underwater vehicles).

Of the considered materials, ceramics have shown the most potential for vehicles with pressure housings in the 4- to 50-inch-diameter range. Existing technology, though, does not lend itself to fabrication of ceramic pressure hulls with diameters greater than 50 inches. Glass, originally considered for the same applications, has been found to be, due to its lower tensile strength, more notch sensitive than ceramic and, thus, more prone to crack initiation at low stress levels.

*All figures and tables are placed at the end of the text.

At the present time, pressure housings with diameters greater than 50 inches for deep submergence service must be fabricated from titanium alloys and their W/D ratio of 0.8 must be augmented with expensive syntactic foam that provides, at best, only one pound of additional buoyancy for each pound of foam. This unfortunate situation may change only if the technology for fabricating graphite fiber-reinforced plastic (GFRP) composites becomes mature enough so that large external pressure housings can be built with confidence. To date, the largest external pressure housing cylinder of GFRP composite for 9,000 psi service measures 30.25 inches outside diameter (OD) by 25.25 inches internal diameter (ID) by 65.0 inches length (L) (reference 1). But even this housing must have titanium hemispherical end closures as no process has yet been devised for fabricating a GFRP composite hemisphere with a W/D ratio lower than that of titanium. It will require a decade of development before the GFRP composite technology is capable of producing external pressure housings for deep submergence service with diameters greater than 50 inches.

To arrive at an operationally usable external pressure housing of ceramic material, several fabrication and design problems needed to be solved that have, in the past, worked against the acceptance of such housings by the ocean engineering community. These problems were (1) selection of inexpensive ceramic composition with optimum structural performance, (2) economical fabrication of large ceramic cylinders, (3) reliable mechanical joining of several ceramic cylinders into a cylindrical pressure housing of desired length, (4) elimination of stress risers on the ceramic bearing surfaces between individual housing assembly components, (5) mounting of payload components inside ceramic cylinders, and (6) protection of the ceramic housing against point impact.

PREMIUM CONSTRUCTION MATERIALS

Extensive research efforts have been undertaken to determine the strengths and weaknesses of various ceramic materials for deep submergence service and to develop suitable designs for external pressure housings (tables 2 and 3). Lightweight materials are required that not only possess

outstanding compressive strength-to-density ratio, but also possess adequate tensile strength to withstand flexure stresses resulting from the handling of these vessels during assembly, shipping, and launch and/or retrieval at sea.

Two such materials have been found in external pressure hulls. *Pyroceram[C] glass ceramic* is a product of the Corning Glass Works, while *CER-VIT[R]* is manufactured by Owens Illinois. They represent a class of materials converted into crystalline ceramic from an original glassy state by the use of nucleating agents and heat treatment. Tests have shown that glass ceramic has an ultimate compressive strength of 350,000 psi. The high compressive strength, when combined with the low density (0.093 pounds/cubic inch) results in a strength-to-density ratio of 3,700,000 that surpasses that of alumina and beryllia ceramics.

Early evaluations of this material by the Ordnance Research Lab of Pennsylvania State University (references 2 and 3) and the Naval Civil Engineering Laboratory (reference 4) concluded that the compressive strength-to-density ratio of glass ceramic is unexcelled and that combined with their intrinsic high moduli of elasticity and ease of fabrication in large shapes (both in length and diameter) make them obvious choices as structural materials for mass production of large pressure housings for deep submergence buoys, oceanographic capsules, and vehicles.

Because of high start-up costs and expensive tooling required for spin casting molten material in the glassy phase, glass ceramics have found no application in pressure housings for undersea vehicles to date. Cost trade-off studies conducted by Corning Glass have shown that it required a minimum production quantity of 500 identical glass ceramic cylindrical housings before the unit cost decreased below that of an alumina-ceramic housing with the same exterior dimensions.

Alumina ceramic, more than any other ceramic composition, has seen extensive structural applications in many technological areas. It has been used successfully in chemical plants as pump components, in electrical power plants as electrical insulators, in mines as grinding mill balls and as linings of ore chutes, and in smelters as linings of furnaces. In addition, it has received extensive evaluation for potential application to oceanographic equipment as deep submergence buoys, and pressure-resistant housings. The tests conducted at Pennsylvania State University with scale-model spherical and cylindrical housing components fabricated from alumina ceramic have shown that alumina ceramic is a reliable structural material from which pressure housings for deep submergence service can be fabricated economically (references 2 and 3).

Beryllia is another ceramic material that has received favorable consideration for external pressure housings. Because of its low density (0.1 lb/in^3) and high compressive strength (~250,000 psi), the strength-to-density ratio of beryllia is 2,400,000. Little experimentation has been done with beryllia as a structural material for external pressure housings because of high cost that surpasses by an order of magnitude the cost of alumina or glass ceramics. The high cost of beryllia ceramic housings is due to the intrinsic cost of material and to the OSHA regulations that must be met while handling the highly poisonous beryllium oxide powder before it is compacted and sintered into solid shapes.

Studies performed at the Naval Command, Control and Ocean Surveillance Center (NCCOSC), RDT&E Division (NRaD) have demonstrated that beryllia ceramic is a reliable structural material with higher thermal conductivity than glass or any other ceramic composition (reference 5). As a matter of fact, the thermal conductivity of beryllia ceramic exceeds the conductivity of many metals, like nickel, titanium, stainless steel, and aluminum. Therefore, there is no doubt that because of its *outstanding heat conductivity*, it will experience extensive application as small, nonmagnetic pressure housings for electronic components generating a lot of heat during operation.

Boron carbide is a ceramic material that possess excellent physical properties, but because of high fabrication costs has not been seriously considered for external pressure housings. This situation may change, however, as more AUVs with high-performance requirements reach the system

definition stage. Boron carbide ceramic has a density of 0.09 lb/in^3, compressive strength greater than 500,000 psi, modulus of elasticity greater than 65,000,000 psi, and flexural strength in the range of 40,000 to 60,000 psi. These physical properties make it feasible to design cylindrical external pressure housings for 9,000 psi service with a W/D ratio of only 0.25; a 50-percent reduction of weight when compared to alumina-ceramic housings with the same pressure service. Again, high cost is a major barrier to using boron carbide ceramics, as fabrication requires that cylindrical or spherical shapes be isostatically pressed in a graphite mold at temperatures over 1000°C. Because of this, the cost of the finished housing is approximately 500-percent higher than that of an aluminum oxide housing of the same dimensions.

Ceramic composites are part of a new family of ceramics made up of several materials joined together by mechanical and/or chemical bonding. Two ceramic composites appear to be promising materials for construction of external pressure housings; boron carbide lattice filled with metallic aluminum (reference 6) and silicon carbide lattice filled with metallic aluminum that has been partially converted to aluminum oxide (reference 7).

As a family, these composites share two major advantages over homogeneous ceramic compositions:

(1) There is very little, if any, shrinkage of ceramic composites during sintering, compared to about 15-percent shrinkage occurring during sintering of homogeneous ceramic compositions. This allows fabrication of ceramic components to final dimensions without having to grind them after sintering.

(2) The fracture toughness of ceramic composites is significantly higher than that of homogeneous ceramic compositions since the boundaries between dissimilar components of the composite act as obstacles to crack propagation.

There is one additional advantage inherent to boron carbide/aluminum composite; its density is only 0.09 lb/in^3, which with its compressive strength of over 300,000 psi provides a specific strength of at least 3,350,000.

After reviewing the physical properties, intrinsic costs, and availability and fabrication processes for each of the four ceramic compositions discussed, the focus for further investigation shifted to alumina ceramics.

Alumina ceramics stand out among the many available ceramic compositions because they present the most choices to the designer at an affordable price. The physical properties of alumina ceramics vary with the percentage of aluminum oxide in the sintered product. As a rule, the compressive, tensile, and flexural strengths as well as the hardness, modulus of elasticity, density, and production costs increase with higher percentages of aluminum oxide (table 4). Experience, however, has shown that the most cost-effective ceramic compositions are those containing 94- to 96-percent aluminum oxide. The physical properties of both ceramic compositions make them structurally superior to the Ti-6Al-4Va titanium alloy currently used in the construction of deep submergence pressure housings (table 5).

What makes these compositions so desirable for fabrication of external pressure hulls for underwater vehicles is the fact that these are the ceramic compositions with the highest percentage of alumina ceramic from which large cylindrical and hemispherical sections of pressure hulls can be fabricated economically. Cylinders with 50-inch diameters have been fabricated from 94-percent alumina, and cylinders with 32-inch diameters have been fabricated from 96-percent alumina- ceramic compositions. Fabrication of cylinders this large has been successful and there are indications that even larger cylinders can be made from these compositions.

The cost of precision-ground pressure housings of cylindrical shapes fabricated from 94- or 96-percent alumina composition is approximately $100 a pound (1989 dollars) in quantities of five or more. This compares very favorably to fabrication costs of graphite, or glass fiber-reinforced plastic composite on a per-pound basis. No comparison can be made at this time between the fabrication costs for ceramic and fiber-reinforced plastic

composite hemispheres, as a process has not yet been developed for producing GFRP composite hemispheres with physical properties comparable to those of cylinders.

To fulfill the need for deep submergence housings with higher payload capability, several cylindrical shell sections can be joined together by mechanically reliable, and structurally strong, metallic joints. It is vital that the joints be able to withstand hydrostatic pressure. It is also important that they be capable of withstanding the bending movements imposed on the cylindrical pressure housing during handling, and launching and retrieval from the ocean. Whenever feasible, the joint should be flush with the exterior surface of the fairing enclosing the housing to decrease the vehicle's hydrodynamic drag.

The ability to form large-diameter monolithic cylindrical housings is very definitely limited by size. The size limit for various materials is imposed by the following restrictions: for alumina ceramics, the *slumping* of green ceramic cylinders and/or hemispheres in the firing kiln during sintering; for glass ceramic, the *nonuniformity of nucleation* in very thick glass sections; and for ceramic composites, the *crushing* of green ceramic cylinders under the hydrostatic pressure of molten aluminum.

However, an approach has been proposed and experimentally validated to increase economically the diameter and length of the cylindrical housings beyond the limits of present technology. This approach relies on forming large cylindrical housings by assembling and brazing together smaller pre-fired, ring-shaped ceramic structural modules (figure 3). The thickness of individual rings is selected by the designer on the basis of a trade-off between the cost of pressing and firing individual rings versus the cost of grinding the parallel bearing surfaces on each ring (i.e., in a cylinder of given length, the cost is determined by the number and production cost of individual rings).

The key to the construction of housings using this method is a reliable, inexpensive bonded joint that (a) transfers high compressive axial stresses without squeezing out the bonding agent, (b) is watertight, (c) has good tensile strength, and (d) deforms sufficiently to eliminate point loadings between adjacent ceramic bearing surfaces. The approach that appears most promising for joining the modules is brazing with specially formulated metallic solder. Because the cost of a monolithic cylinder is significantly less than that of a cylinder with identical dimensions fabricated by the brazing of many rings, this construction technique becomes cost effective only if the cylinder is so large that it is beyond the state of the art for existing ceramic technology (i.e., >50 inches in diameter and 30 inches in length). Since all the pressure housings required by the NRaD ceramic housing program could be economically fabricated from monolithic cylinders and hemispheres, modular construction was not further pursued in the program for third generation ceramic housings.

HOUSING DESIGN

Once a material has been selected for the housing construction, the matter of design must be considered. The collapse resistance of any housing is dependent upon the shape of the shell. The two most common shapes used in oceanographic research are the sphere and cylinder. Spheres are used in applications where the hydrodynamic drag of the structure moving through the water is not important. However, if it is desirable that the submersible move quickly through hydrospace, such as in a free-diving oceanographic instrumentation capsule, remotely operated vehicles (ROVs), or autonomous underwater vehicles (AUVs), a cylindrical shape is more appropriate.

The simplest type of cylindrical shell is the *monocoque cylinder* capped at the ends with hemispheres (figure 4). For design pressure ≥9,000 psi, where thick walls are required not only because of the cylinder's low elastic stability, but also because of high stress loading of the cylinder wall, the monocoque cylinder provides an inexpensive shell design with fair W/D ratio. It is used when some structural efficiency can be sacrificed in exchange for decreased cost in fabrication.

To make a cylindrical housing elastically more stable under external pressure loading without increasing its wall thickness, it is necessary to incorporate radial support (figure 5). Four basic

cylinder designs exist: (1) monocoque shell, (2) monocoque shell with integral end stiffeners, (3) monocoque shell with an integral midbay stiffener in addition to those on the ends (references 2, 3, and 4), and (4) monocoque shell supported at frequent intervals with integral stiffeners along its full length. Another potential approach to providing radial support to monocoque cylinders is to bond a metallic stiffener to the interior surface of the cylinder at midbay (figure 6) or to place a removable metallic stiffener at the end of the cylinder that also acts as a joint between adjacent cylinders (figure 7).

To fulfill the need for longer deep submergence housings, several cylindrical shell sections must be joined together by mechanically reliable, and structurally strong metallic joints. It is vital that the joints be able to withstand hydrostatic pressure. It is also important that they be capable of withstanding the bending moments imposed on the cylindrical pressure housing during handling, and launching and retrieval from the ocean. Whenever feasible, the joint should be flush with the exterior surface of the fairing enclosing the housing to decrease the vehicle's hydrodynamic drag. *Only if the requirement for reliable mechanical joints capable of repeatedly withstanding high compressive stresses without the initiation of fractures in the ceramic components has been successfully met would ceramic housings be considered a viable alternative to metallic housing.*

To meet this requirement, the designer of the joint will have to consider the loadings on the ceramic cylinder ends introduced by the mismatch in radial stiffeners, Poisson's ratio, coefficient of thermal expansion, and hardness and surface of finishes between the end of the ceramic cylinder and the metallic joint ring (figure 8). Because of their importance, a significant portion of the NRaD ceramic program was devoted to design and evaluation of mechanical joints.

BACKGROUND INFORMATION

The Navy's ceramic pressure housing program was initiated in 1982 as part of the NOSC Independent Research/Independent Exploratory Development (IR/IED) Program in deep ocean technology. Since that time, it has received continuous support not only from the IED Program, but also from other Navy activities. The program was planned from the beginning to progress in an orderly fashion from small to large housings, and from short to long housings. Each phase of the program focused on specific problems that needed to be solved prior to proceeding further with development of ceramic housings. Three phases have been completed and are summarized in the following paragraphs.

PHASE 1, SUMMARY: FIRST GENERATION OF CERAMIC HOUSINGS

The first phase of the program focused on evaluation of (1) beryllia ceramic as the potential choice of material for construction of external pressure housings and (2) the structural concept of monocoque ceramic cylinders supported radially at the ends by spherical, or plane, end closures (reference 5).

Tests performed with 6.039-inch OD by 9-inch L by 0.207-inch t cylinders in which the ceramic was *subjected to a compressive stress of* 150,000 psi have shown that beryllia ceramic is an acceptable structural material for external pressure housings, except for its high cost. The high cost is, however, tolerable for some applications where the high thermal conductivity of beryllia is an absolute operational requirement (0.65 cal/sec cm^2 C°/cm).

Tests have shown that the structural concept of monocoque ceramic cylinders supported radially at their ends by removable metallic end closures is valid. The elastic instability of the monocoque ceramic cylinders (i.e., buckling) was predictable on the basis of the BOSOR computer program analysis. The tests, however, also highlighted one facet of the concept that needed further improvement before this concept could be considered acceptable for the design of external pressure housings.

The original concept of bare ceramic cylinders supported at their ends by metallic hemispherical end closures was found to have a cyclic fatigue life of less than 30 pressurizations to design pressure. The failure of cylinders was initiated by fretting of

the bare, plane ceramic bearing surface after it came in contact with the plane bearing surface on metallic hemispheres. The fretting rapidly progressed to major spalling and, ultimately, implosion (figure 9). Unless the cyclic fatigue life could be extended to a minimum of 100, and preferably 500, pressurizations to design pressure, this design concept would see only very limited application to pressure housings on ROVs and AUVs. The extension of fatigue life could only be achieved by total, or partial, elimination of fretting on the ceramic bearing surfaces in direct contact with metallic end closures.

Other tests have shown that monocoque cylinders of polylithic construction performed identically to monocoque cylinders of monolithic construction. No difference was found in the structural performance between polylithic cylinders whose cylindrical segments were joined either by epoxy adhesive, or by nickel brazing. In either case, the polylithic cylinders successfully passed the 10,000-psi proof test like the monolithic cylinder of identical dimensions. The distribution of strains on the ceramic was identical in all three cases.

PHASE 2, SUMMARY: SECOND GENERATION OF CERAMIC HOUSINGS

The second phase of the program focused on the following areas: (1) evaluation of alumina ceramic for construction of external pressure housings, (2) elimination, or reduction, of fretting on ceramic bearing surfaces in contact with metallic end supports, and (3) joining of cylindrical housing sections to form a long housing assembly (reference 8).

The 6-inch OD by 9-inch L cylinders were fabricated from 94- and 99-percent alumina ceramic. The hemispherical bulkheads and joint rings were machined from Ti-6Al-4Va alloy. Tests showed that both 94- and 99-percent alumina ceramic performed satisfactorily at compressive stresses in the range of –130,000 to –150,000 psi. In addition, the elastic instability (i.e., buckling) of monocoque simply supported cylinders was predictable by the BOSOR computer program analysis for buckling of monocoque tubes. The 94-percent alumina cylinders with $L/_D = 1.5$ and $t/_D = 0.0345$ catastrophically failed at approximately 17,5000 psi when radially supported at the ends with thick plane bulkheads. When hemispherical titanium bulkheads with 20,000-psi critical pressure were substituted for plane bulkheads, the cylinders failed by buckling at approximately 14,250 psi.

The fretting of ceramic bearing surfaces was reduced by enclosing the ends of ceramic cylinders with metallic end caps. Epoxy-filled end caps protect the ceramic bearing surfaces from fretting due to differential displacement between the ceramic cylinder and metallic end closures (figure 10). The 0.001-inch-thick layer of epoxy between the ceramic surfaces on the ends of the cylinder and the metallic end caps not only eliminates any differential displacement between the mating ceramic and metallic surfaces, but also serves as a compliant bearing gasket for the plane and radial ceramic surfaces.

The metallic end caps were fabricated from alloy of which the compressive yield strength exceeded 65,000 psi. Both Ti-6Al-4Va and 7178-T6 alloys were used. For satisfactory performance, the radial clearance between the end caps and the ceramic surfaces was maintained at <0.010 and the depth of the seat in the end caps $>1.44t_c$ where t_c is the thickness of cylinders. Neither fretting nor spalling were observed on the ends of ceramic cylinders after 3,000 pressure cycles to 9,000-psi design pressure.

Brazing together several-inch-wide cylindrical segments (i.e., rings) into pressure housings was found to be a structurally acceptable technique for fabricating polylithic monocoque cylinders whose length exceeded the limitations of the fabrication process for monolithic cylinders of a given diameter. The cost, however, was found to be two- to three-times higher than for fabricating monolithic monocoque cylinders of the same length and diameter, and, for this reason, polylithic construction is not considered to be a cost-effective approach for making long monocoque cylindrical sections. A less-expensive approach appears to be joining cylindrical sections with removable, or fixed, metallic couplings.

Ceramic cylinders were joined successfully with removable metallic joint rings that provided simple radial support to the ends of adjoining cylinders. To

prevent buckling of the monocoque ceramic cylinders, the joint ring had to act as a stiffener that would raise the critical pressure of the two adjoining monocoque ceramic cylinders to 13,500 psi. This was successfully accomplished with a T-shaped stiffener design machined from Ti-6Al-4Va alloy. No efforts were made to optimize the shape of the stiffener in order to minimize its weight.

PHASE 3, OVERVIEW: THIRD GENERATION OF CERAMIC HOUSINGS

The following chapters in this report describe in detail the objectives, test specimens, test procedures, and test results of the program leading to the development of third generation ceramic housings. Because the program extended over several years and covered many technical areas, the description of the program, test results, and findings are grouped into six chapters, each focusing on a different area of investigation.

These areas are

1. Overview of the program.
2. Summary of findings, conclusions, and recommendations.
3. Design and testing of 6-inch-diameter scale-model ceramic housings for validation and optimization of ring stiffener concepts (appendix A).
4. Design and testing of 12-inch-diameter full-scale ceramic housings for validation of geometric scaling factors and mechanical joint concepts (appendix B).
5. Design and testing of 12-inch-diameter full-scale ceramic housings for validation of ceramic hemispherical end closure designs with single and multiple penetrations (appendix C).
6. Design and testing of end caps with improved cyclic fatigue life for 12-inch-diameter ceramic cylinders and hemispheres (appendix D).
7. Nondestructive inspection of ceramic cylinders prior to, and after, pressure cycling 12-inch-diameter housings (appendix E).

Chapters 3 through 7, because of their length and number of figures, have been placed into separate appendices, A through E. Only Chapters 1 and 2 are in the main body of the report.

THIRD GENERATION CERAMIC HOUSING PROGRAM

OVERVIEW

Objective

The primary objective of the third generation ceramic housing program was to make the concept of alumina-ceramic housings acceptable for service as primary pressure hulls in ROVs and AUVs. To accomplish that, it had to be demonstrated that

1. The structural performance of the ceramic cylindrical housing components does not degrade when their size is increased by 100 percent from scale-model 6-inch OD by 9-inch L by 0.207-inch t to full-scale 12-inch OD by 18-inch L by 0.412-inch t cylinders.
2. The heavy metallic hemispherical end closures can be replaced with lighter, but stronger, ceramic end closures incorporating penetrations capable of accommodating electrical and hydraulic feedthroughs.
3. The ceramic cylinders and ceramic, or metallic, end closures can be mechanically joined into a single pressure-resistant structure of which the critical pressure can be accurately predicted by the BOSOR4 computer program.
4. The ceramic components can withstand without breakage point impacts of up to 100 foot-pounds of kinetic energy when protected with a simple elastomeric coating.
5. The length of the housing can be extended without reduction of critical pressure either by joining several *short* cylindrical sections with removable metallic joint ring stiffeners, or by extending the length of a single monocoque cylinder and subsequently stiffening it

internally with metallic rings bonded to the interior surface of the cylinder at appropriate intervals.

Approach

To meet the objective in a cost-effective manner, 6-inch and 12-inch-diameter ceramic housings were subjected to short-term and cyclic pressurizations. The 6-inch-diameter cylinders served as test specimens for experimental evaluation of midbay and end stiffeners of different configurations and materials. The 12-inch-diameter cylinders served as test specimens in the (1) validation of scaling factors used in extrapolation of dimensions from the 6-inch scale-model to 12-inch full-scale cylinders, and (2) demonstration of replacing titanium hemispherical end closures with ceramic hemispheres incorporating one, or many, penetrations capped with bulkhead penetration inserts.

Test Specimens

The 6-inch- and 12-inch-diameter cylinders and hemispheres were fabricated by Coors Ceramics from 94-percent alumina ceramic (table 1). The metallic end closures of the 6-inch- and 12-inch-diameter ceramic housings were machined from Ti-6Al-4Va alloy with 125,000-psi yield strength. The end caps for cylinders and hemispheres, the penetration inserts, as well as the joint ring stiffeners also were machined from the same titanium alloy. Aluminum alloy 7075-T6 with 65,000-psi yield strength was used in some cases for fabrication of cylinder end caps and stiffeners to evaluate it as a potential replacement for the more expensive titanium alloy. The test specimens and their dimensions are listed on table 6.

Design Criteria

To meet the objectives of the program with a minimum of test specimens and least expenditure of funds, the following design criteria were followed:

1. *The ceramic composition* selected for all ceramic components was 94-percent alumina ceramic, as it provided that highest specific compressive strength and modulus of elasticity at the lowest cost for a fabricated specimen. Other ceramic compositions like SiC, SiN_2, and B_4C have much higher specific compressive strength, but the costs of fabricating cylinders and hemispheres are, in most cases, 500- to 600-percent higher. Thus, their application must be reserved for critical Navy applications where the high cost of the premium ceramic housing material can be justified by operational requirements that can be met *only* by pressure housings with a W/D ratio >0.3.

   Substitution of 96-, 98-, and/or 99.5-percent alumina compositions for the 94-percent composition used in the 6- and 12-inch test specimens would have resulted in pressure housings with 5- to 10-percent weight saving at a 20- to 50-percent increase in cost. The reason for not selecting these premium compositions for the 6- and 12-inch test specimens was the inability of the industry in the time frame that this program was conducted to fabricate cylinders and hemispheres larger than about 20 inches from these materials without an extensive development program.

   Since the end objective of the NOSC ceramic housing program was to provide design criteria and to evaluate the applicability of existing fabrication procedures to manufacture ceramic housings with 50- to 60-inch diameters, there was no point in fabricating the 6- and 12-inch ceramic housing test specimens from alumina-ceramic compositions that could not be applied to fabrication of pressure housings in operationally useful sizes without being preceded first by a long and costly development program.

2. *A thickness-to-diameter* (t/D_0) ratio of 0.034 was the same for 6- and 12-inch-diameter cylindrical test specimens. It was chosen to satisfy the design requirement that the maximum compressive stresses in the cylinders fall into the 130,000- to 150,000-psi range. This conservative stress level represents a safety factor (SF) of 2 based on the typical 300,000-psi compressive strength of 94-percent alumina ceramic. Although published reports indicate that alumina-ceramic cylinders and spheres have been stressed to

levels above 200,000 psi without failure, it was decided to limit the stresses to 150,000 psi since the alumina-ceramic housings could tolerate larger voids without initiation of cracking at the lower stress level.

The 150,000-psi maximum design stress level also was chosen for 12-inch ceramic hemispheres. The peak stress levels exceeded their values only in Hemisphere Mod 3, where the peak stresses at the edge of penetrations were calculated to reach 295,000 psi.

3. *A thickness-to-length* (L/D_o) ratio of 1.5 between radial supports was the same for all cylinders. It was chosen to satisfy the design requirement that the failure of the cylinders, if supported radially at the ends by rigid bulkheads, would occur at approximately 18,000 psi. This represents an SF of approximately 2 based on elastic instability. Because the magnitude of the SF for buckling matches the SF for material failure, the compressive strength of the ceramic would be used to the maximum prior to failure, provided that the radial supports were designed to maintain their circularity to 18,000-psi external pressure loading.

4. *Radial support* provided to the cylinders by bulkheads, or ring stiffeners, varied depending on the objective of the test to which the test specimen was submitted. For housings representing operational configuration for a design depth of 20,000 feet, the radial support was designed to provide elastic stability only to 11,250-psi pressure loading, representing a 25-percent overpressure over design depth. The 1.25 SF for buckling was considered a good trade off between weight of the radial supports (i.e., bulkheads and stiffeners) and the safety margin that they provided against buckling of the precision-ground cylinders since it has been shown that the critical pressures of precision-ground cylinders deviate less than 10 percent from calculated values.

Thus, for housing assemblies that (a) represented operational configurations and (b) were slated for testing to pressures ≤10,000 psi, the titanium and ceramic hemispherical end closures, or ring stiffeners, were designed to provide elastic stability only to 11,250 psi.

In addition to the lightweight titanium hemispherical end closures with a 1.25 SF, heavier titanium hemispherical end closures with a 1.55 SF for 9,000-psi design pressure also were fabricated. The heavier hemispheres saw service in those housings that, due to requirements of the user, had to be proof tested to pressures greater than 10,000 psi. Housing assemblies slated for destructive testing were provided with massive, flat-end closures capable of providing radial support to external pressures exceeding 20,000 psi.

5. *Finite element computer analysis* was employed to verify the magnitude of stresses in the hemispherical end closures and joint ring stiffeners. The BOSOR4 program was used to check the elastic stability of whole-housing assemblies. The optimization of individual joint ring stiffeners was performed empirically (i.e., the holes in the webs of stiffeners were enlarged until the assembly failed at 10,000 psi pressure). The empirical approach was considered to be significantly less expensive and more reliable for this application than a computer program capable of predicting accurately the elastic instability of ring stiffeners with lightening holes in the stiffener webs.

6. *The adhesive system* selected for bonding the metallic end caps to the ceramic components was identical to the one selected for the NOSC second generation ceramic housings (70 parts of CIBA Geigy 283 hardener with 100 parts of CIBA Geigy 6010 resin). There was no reason to change the adhesive system as (a) adhesives with better structural performance were not found in technical literature, and (b) Martin Marietta Aero and Naval Systems had performed extensive experimental evaluation of a commercially available resin bonding system for their ceramic MUST pressure hull and also did not find any resin system with structural performance superior to the one used by NOSC (table 7). The

0.010-inch-thick cardboard spacers used between the plane-ceramic bearing surfaces of cylinders or hemispheres and the metallic end caps were also identical to those used in the 6-inch-diameter NOSC first generation housings. By keeping both the adhesive system and the spacer material identical to those in the NOSC first generation housings, these items were *not* variables in experimental evaluation.

7. *The end caps* on the 6-inch ceramic cylinders were identical to those on the 6-inch-diameter cylinder of the NOSC second generation housings that successfully withstood 1,000 pressure cycles to 9,000 psi without initiation of cracks on the bearing surfaces (reference 8). This was not the case with the end caps on the 12-inch-diameter ceramic cylinders and hemispheres. The design of the end caps on the 12-inch components did not follow the linear scaling law in all dimensions; *instead of enlarging the exterior lip of the cap* to 0.700 of an inch (0.350 inch x 2), it was made only 0.350 of an inch deep, the same size as those on the 6-inch cylinders. The interior lip was increased to 0.63 of an inch, but even this lip fell short of the 0.7-inch dimension to which it should have scaled up.

   The reasons for making the lips on the end caps shorter than the linearly extrapolated dimensions were twofold: (a) there was a need to keep the weight of the metallic components down and (b) it was thought that the length of the lips on the caps did not affect significantly the fatigue life (defined here as the appearance of surface spalling above the edges of the end caps) of the plane-ceramic bearing surface. Test data generated during the course of this program have shown that this is not the case; i.e., the depth of the annular cavity defined by the length of the lips on the cap very definitely affects the performance of the ceramic bearing surface.

8. *Hemispherical ceramic* bulkheads served as specimens in tests where the feasibility of ceramic bulkheads was to be demonstrated. The 6-inch-diameter ceramic hemispheres served only to demonstrate the feasibility of removable ceramic bulkheads for providing adequate radial support to the ceramic cylinder; for this reason, their design was not optimized. After successful demonstration of the structural performance of 6-inch-diameter ceramic hemispheres, full-size 12-inch ceramic hemispheres were designed, fabricated, and tested. The full-size hemispheres incorporated penetrations for bulkhead inserts. The objective of the design was to demonstrate that by replacing titanium hemispherical bulkheads with ceramic ones the weight of the ceramic housing may be reduced, while its critical pressure is increased.

9. *Joints* between cylinders and/or cylinders and hemispheres were designed to perform three functions: seal, fasten, and line up the sections of the housing during assembly. In addition, they were to mate with removable ring stiffeners that provided radial support to the ends of individual cylinder sections. The fasteners were not to extend outside the jackets on the exterior of the cylinders while, at the same time, provide adequate restraint against separation of cylinder sections during launch and retrieval of the operational cylindrical housing assembly at sea.

PHASE 1, SUMMARY OF 6-INCH CERAMIC HOUSINGS

Eleven scale-model cylinders were incorporated into nine different test configurations and subjected to 4,180 pressurizations to 9,000 psi and 13 proof tests to 10,000 psi (appendix A). At the conclusion of the pressure-cycling program, they were tested to destruction.

The *basic* test configuration consisted of a single 6-inch OD by 9-inch L ceramic cylinder of which the ends were protected by metallic end caps and supported by titanium hemispherical bulkheads (figure 11). Subsequently, the titanium hemispherical bulkheads were replaced with ceramic hemispherical bulkheads (figure 12).

The *more advanced* test configurations consisted of several 6-inch OD by 9-inch L ceramic cylinders

assembled in housings incorporating two, or more, cylindrical sections. Removable stiffeners provided not only radial support to the cylinder ends, but also kept them lined up during, and after, assembly into a housing (figure 13). The largest housing test configuration was assembled with four cylindrical sections, three joint stiffeners, and two hemispherical bulkheads (figure 14). In some test configurations two short 6-inch OD by 9-inch L cylindrical sections were replaced with a single, long 6-inch OD by 18-inch L cylinder supported radially at midbay by an internal, metallic ring stiffener bonded to the interior surface of the cylinder with epoxy adhesive (figure 15).

Findings

1. *Ceramic hemispherical bulkheads* can successfully replace titanium hemispherical bulkheads. The ceramic hemispheres with t/D_0 = 0.0308 thickness and W/D = 0.81 weight, when capped with a titanium ring, provided the 94-percent alumina cylinder (t/D_0 = 0.0344 and L/D_0 = 1.5) with sufficient radial support to withstand 14,250 psi prior to implosion by buckling. This represents a 40-percent reduction in weight over titanium hemispheres providing radial support of identical magnitude as the ceramic hemispheres (i.e., providing the ceramic cylinder with 14,250-psi critical pressure).

2. *Removable joint ring stiffeners* can be designed to provide ceramic cylinders with the same elastic stability as plane bulkheads at a fraction of their weight. Removable joint ring stiffeners with elliptical lightening holes provide the ceramic cylinder sections in a housing assembly with the same, or greater, elastic stability than lightweight, operational titanium hemispheres, but at a lesser weight.

   Using the removable joint ring stiffeners, *many* short cylindrical monocoque sections can be assembled between hemispherical bulkheads into a single, long cylindrical housing with the same resistance to buckling (i.e., critical pressure) as a *single* section supported at both ends by hemispherical bulkheads (figure 13). Housing assemblies with one to four ceramic cylindrical sections joined by removable ring stiffeners and closed at the ends with titanium hemispheres (Model 1) have achieved a W/D_0 = 0.57 at 9,000-psi design pressure with a 1.25 SF (figure 14).

3. *Fixed ring stiffeners*, bonded to the interior of long monocoque ceramic cylinders, can provide the same resistance to buckling as *short* monocoque cylinders supported at the ends by removable joint stiffeners (figure 15). Unlike removable joint rings, fixed ring stiffeners can be fabricated from inexpensive, lightweight aluminum, or magnesium, alloys. This is because fixed ring stiffeners do not come in contact with seawater, nor ar they subjected to axial bearing stresses. Furthermore, because the fixed internal ring stiffeners do not require end caps and the external split clamp associated with removable joint ring stiffeners, a housing incorporating a single, long monocoque-ceramic cylinder internally reinforced by fixed ring stiffeners is approximately 7-percent lighter than a housing of identical length made up of two, or more, short cylindrical sections radially stiffened by joint ring stiffeners.

4. *Metallic end caps*, bonded to the ends of ceramic cylinders and/or ceramic hemispheres with epoxy adhesive, protect the bearing surfaces from fretting caused by differential displacement between the ends of ceramic components and the metallic bulkheads or joint ring stiffeners. The cyclic fatigue life of plane bearing surfaces on the ends of cylinders of 94-percent alumina was found to exceed 1,000 pressure cycles at 65,000-psi axial bearing stress loading when protected by titanium end caps with an annular seat of 1.5 t_c depth, where t is the thickness of the ceramic shell. The thickness of the adhesive layer did not exceed 0.010 of an inch.

5. *Metallic brazing* of alumina-ceramic rings results in joints that are not only watertight, but also capable of withstanding 1,000 axial-load applications of 65,000-psi magnitude without separation.

6. Critical pressures generated experimentally by buckling of ceramic monocoque cylinders agree within 10 percent with critical pressures calculated on the basis of analytical expression developed by R. von Mises for simply supported monocoque cylinders of finite length.

    a. For monocoque cylinders supported radially at the ends by plane bulkheads or ring stiffeners, one must use the distance *between supports* in the equation, not the overall length of the cylinder.

    b. For monocoque cylinders supported at the ends by hemispherical bulkheads, one must use the *overall length* of the cylinder plus $D_o/3$ in the equation, not the distance between flanges on the hemispheres.

    The critical pressure of 94-percent alumina monocoque cylinders with $t/D_0 = 0.034$ and $L/D_0 = 1.5$ was found to be $17.500 < p_c < 18{,}000$ psi when supported by plane bulkheads, and $14{,}000 < p_c < 14{,}500$ psi when supported by ceramic hemispherical bulkheads.

PHASE 2, SUMMARY OF 12-INCH CERAMIC HOUSINGS

Scope

Seven ceramic full-scale cylinders and *five* hemispheres were incorporated into a total of *fifteen* different test configurations. They were subjected to 820 pressure cycles to 9,000 psi and 15 proof tests to 10,000 psi. At the conclusion of the pressure-testing program, all of the ceramic specimens that survived the pressure cycling were tested to destruction.

The *basic* components of housings (figures 16 and 17) used for the evaluation of mechanically fastened joints between (1) ceramic cylinder sections and (2) ceramic cylinders and hemispherical bulkheads consisted of 94-percent alumina-ceramic cylinders with adhesive-bonded titanium end caps (figures 18 and 19), joint ring stiffeners (figure 20), and split wedge band clamps (figure 21). The dimensions of the 12-inch OD by 18-inch L by 0.412-inch t ceramic cylinder were arrived at by scaling up, by a factor of two, the dimensions of the 6-inch OD by 9-inch L by 0.206-inch t cylinders tested in Phase 1 of the test program. The dimensions of the *joint ring stiffeners* were also arrived at by scaling up the dimensions of the joint ring stiffeners in the 6-inch-diameter housing assembly.

The *end cap* was the only component of the joint in the 12-inch housing that was not scaled up from the dimensions of the 6-inch-diameter housing (figure 22). While the depth of the annular seat in the 6-inch-diameter end cap was 1.5 t inch, the depth of the seat in the 12-inch-diameter end cap was only 0.58 t inch. The reason for not dimensioning the height of flanges on the 12-inch-diameter end cap by extrapolation of flange height on the 6-inch-diameter end cap was the lack of appreciation for the effect of seat depth on the cyclic fatigue life of the joint.

All *ceramic hemispherical bulkheads* were designed to displace radially under external pressure at the same rate as the ceramic cylinders with $t/D_0 = 0.0343$. This resulted in all hemispheres having a $t/D_0 = .017$ at the equatorial joint. Where they differed, however, was in (1) the number, location, and size of penetrations and (2) the configuration of shell curvature and thickness at penetrations. Five different hemisphere configurations were evaluated.

Titanium hemispherical bulkheads were used primarily in the testing of housing configurations incorporating one, or more, removable joint ring stiffener (figure 19). Two types of titanium bulkheads were available for testing. Type 1 had a design depth of 9,000 psi with a 1.25 SF, and Type 2 had a design depth of 16,100 psi with a 1.25 SF. The reason for using titanium, instead of ceramic, hemispherical bulkheads in pressure housings incorporating removable joint ring stiffeners was to ensure that implosion of the housing during pressure cycling was the result of stiffener buckling and not the cyclic fatigue of the ceramic bulkheads.

Joint ring stiffeners were designed and fabricated from either Ti-6Al-4Va, or 7178-T6 alloys

(figure 20). The reason for evaluating ring stiffeners from both alloys was to provide the potential user of ceramic housings with a choice between two stiffener configurations. One alloy was for pressure housings under long-term submersion, and the other was for short-term submersions where the corrosion resistance of titanium is not required.

Joint split band clamps were fabricated either from 6061-T6 aluminum or Ti-6Al-4Va titanium alloys (figure 21). Split band clamps machined from aluminum are considered to be strong enough to carry tensile stresses generated by bending movements during the handling or lifting of a ceramic housing assembly made up from as many as four sections. Since contact with titanium end caps generates galvanic corrosion, titanium split band clamps were used in tests where the housings were submerged in seawater for long periods of time.

Findings

Removable Joint Ring Stiffeners

1. *Removable joint ring stiffeners* sized by linear scaling of the dimensions on stiffeners in the 6-inch-diameter model housings perform structurally in an identical manner to scale-model stiffeners (figure 22). Since their radial stiffness exceeds that of a ceramic cylindrical shell, bending stresses are introduced in the ceramic shell near the joint stiffeners. Their magnitude, however, is small. For this reason, the principal stresses in hoop and axial directions at that location were all found to be negative (figure 23).
2. The magnitude of stresses recorded on the joint ring stiffeners was found to be a function of stiffener design. On titanium joint stiffeners *without* any lightening holes in their webs, the *tensile stresses* at 10,000-psi proof pressure were found to be less than 25,000 psi, *the compressive stresses* were less than –35,000 psi, and the *bearing stresses* were less than –70,000 psi.
3. On *aluminum* joint stiffeners without any lightening holes in their webs, the tensile stresses at 10,000-psi proof pressure were found to be less than 12,000 psi, the compressive stresses were less than –32,000 psi, and the bearing stresses were less than –70,000 psi. In this case, the boaring stresses were equal to the yield strength of the 7178-T6 aluminum alloy from which the stiffeners were machined. This, however, did not present any problems as the thin stiffener web trapped between the mating titanium end caps on the cylinders could not extrude radially because of radial restraint imposed on it by external hydrostatic pressure.
4. On the stiffeners with lightening holes, the tensile and compressive stresses increase as a function of hole size in the stiffener web. When the lightening holes are too large, buckling of the inner flange takes place below proof pressure. However, if the holes machined into the stiffener web are kept below critical size, the stiffeners retain their structural integrity at 10,000 psi while providing a weight reduction of 5 percent.
5. Since the small reduction in weight of the stiffener is accompanied by a large reduction in elastic stability, the machining of holes in the ring stiffeners does not appear to be a cost-effective way of reducing the weight of the stiffeners. Their effectiveness lies mainly in serving as penetrations for electric, or hydraulic, lines inside the ceramic housing.

Ceramic Cylinders

1. The 12-inch-diameter ceramic cylinders sized by linear scaling up of dimensions on the 6-inch-diameter ceramic cylinders perform structurally in a similar manner to the scale-model cylinders. Maximum stresses recorded on the internal surface at midbay were –137,000 psi (0.3-percent strain) in hoop direction and –67,000 psi (0.09-percent strain) in axial direction.
2. The hoop stresses on the internal surfaces of a cylinder decrease by 5 percent near the radial support provided by the hemispherical bulkheads and joint ring stiffener. This indicates that the radial compliance of the support

provided by the bulkheads and the stiffeners to the ceramic cylinder is well matched to the radial contraction of the cylinder under external hydrostatic pressure.

3. When pressurized to implosion while supported radially by plane-steel bulkheads, the 12-inch ceramic cylinders failed in the same range of pressures (i.e., 17,000 to 18,000 psi) as the 6-inch scale-model cylinders. This confirms the postulate that the scaling up of 6-inch-diameter ceramic cylinders by a factor of two does not result in reduction of critical pressure providing that (1) the maximum membrane hoop stress at critical pressure does not exceed –273,000 psi and that (2) the voids inside the ceramic shell do not exceed 0.05 inch in diameter.

4. The safety margin between the design pressure of 9,000 psi and the critical pressure for 12-inch-diameter cylinders is approximately 100 percent, even though sonic nondestructive evaluation (NDE) had detected some voids with dimensions in the 0.015- to 0.05-inch range beforehand in the shells of the 12-inch cylinders.

5. The W/D ratio of 12-inch-diameter 94-percent alumina-ceramic cylinders with $t/D_0 = 0.0343$ and $L/D_0 = 1.5$ is 0.51 when equipped with Mod 0 titanium end caps, or 0.48 when equipped with end caps made from 7178-T6 alumina.

Ceramic Hemispheres

1. Penetrations can be incorporated successfully into ceramic hemispheres without reducing their elastic stability (figure 24). The size of the largest penetration successfully incorporated into the 12-inch-diameter hemispheres was defined by $d/D_0 = 0.25$, where d and D_0 are the diameters of penetration and hemisphere, respectively.

2. It is not known at the present time how many penetrations a hemisphere may tolerate at proof pressure without catastrophic failure. Successful performance at proof pressure of hemisphere Model 5 with five penetrations has shown, however, that hemisphere designs with evenly spaced penetrations are acceptable provided that the separation between edges of penetrations exceeds the radius of the larger of the adjoining penetrations.

3. Point, or line, contact between metallic penetration inserts and the ceramic shell surface can be eliminated successfully by placing contoured laminated phenolic washers underneath the flanges of penetration inserts (figure 25).

4. All stresses in the ceramic hemispheres are of a compressive nature, and their peak values are a function of shell design. Without any reinforcements around the penetrations, peak compressive stresses of –278,000 psi magnitude were recorded. With properly designed reinforcement around the penetration, the peak compressive-stress value can be reduced to –138,000 psi membrane-design stress.

5. The principal compressive stresses in the ceramic hemispheres at the equatorial joint are significantly higher than in the ceramic cylinder (figures 26 and 27). Also, since the spherical shells are 50-percent thinner than the cylindrical shells, the resulting axial bearing stress on the plane equatorial surface of the hemispheres is 100 percent higher than on the cylinders (figure 28). This makes the plane bearing surface of hemispheres more susceptible to the initiation of cracks under repeated pressurizations.

6. The W/D ratio of 12-inch-diameter 94-percent alumina-ceramic hemispheres equipped with titanium Mod 0 end rings and connector inserts varies from *0.46* to *0.80* depending on hemisphere configuration and number of penetrations. The critical pressure of ceramic hemispheres is ≥20,000 psi.

Titanium Hemispheres

1. The 12-inch-diameter Type 1 titanium hemispherical bulkhead for 9,000-psi design depth performs satisfactorily up to its proof test

depth of 10,000 psi (figure 29). Maximum compressive membrane stress recorded at proof test depth is −100,000 psi. This indicates that, if pressurized to destruction, the implosion pressure will exceed the specified critical pressure of 11,250 psi. The W/D of the Type 1 hemispherical bulkhead is 0.75. It represents the lowest W/D ratio for 9,000-psi design depth achievable safely with titanium hemispherical bulkheads.

2. The 12-inch-diameter Type 2 titanium hemispherical bulkhead for 16,100-psi design depth performs satisfactorily up to its proof test depth of 17,900 psi. Maximum compressive membrane stress recorded at proof test depth is −100,000 psi. This indicates that if pressurized to destruction, the implosion pressure will exceed the specified critical pressure of 22,500 psi. The W/D of the Type 2 hemispherical bulkhead is 1.45.

3. The joint between the titanium hemispherical bulkhead and the ceramic cylinder performed satisfactorily to the 10,000-psi proof test depth (figure 30). The split wedge band used for fastening the Type 1 titanium hemisphere to the ceramic cylinder was identical to the bands used for fastening other joints to the 12-inch ceramic housing.

End Caps

1. Mod 0 end caps did not provide the ends of 12-inch-diameter ceramic cylinders and hemispheres with the same protection against the initiation and propagation of cracks on the plane-ceramic bearing surfaces as did the end caps on the scale-model 6-inch-diameter cylinders. While spalling was not visible on the exterior surfaces of scale-model cylinders after 2,000 pressure cycles to 9,000 psi, it was apparent on the external surfaces of the 12-inch cylinders and hemispheres and, in some cases, after only about 30 cycles (figure 31).

2. The cyclic fatigue cracks originating on the plane-ceramic bearing surfaces of cylinders and hemispheres propagate circumferentially and axially into the shells of the ceramic components, forming fracture surfaces that parallel the external curvature of the shell (figure 32). The fracture surfaces may grow to a depth of several inches before (a) the ceramic component weakens from the formation of layers and implodes unexpectedly at a pressure that is significantly lower than the design pressure (figure 33), or (b) the fracture surface breaks through the exterior or interior surfaces of the shell causing it to leak.

3. Tensile, principal stresses on the plane-bearing surfaces of ceramic components cause cracks to initiate under cyclic pressure loadings. The magnitude of principal tensile stresses at these locations is a function of joint configuration, axial compressive bearing stress, and the magnitude of difference in the physical properties of materials compressing the joint structure. The magnitude of tensile stresses on the plane-bearing surfaces of ceramic components encapsulated with epoxy in Mod 0 titanium end caps has been calculated by finite element analysis (FEA) to be in the range of 5,000 to 6,000 psi for joints between ceramic cylinders, and 11,000 to 13,000 psi for joints between ceramic cylinders and ceramic hemispheres (figures 34 and 35).

4. Increasing the depth of the annular seat in the end cap (i.e., height of flanges on the end cap) for cylinders or hemispheres reduces the magnitude of tensile stress on the plane-ceramic bearing surfaces. This, in turn, delays the initiation, and retards the rate of propagation, for the cyclic fatigue cracks on these surfaces.

5. The Mod 1 end caps (figure 36) for 12-inch-diameter cylinders formed by increasing the depth of the seat from 0.245 inch to 1 inch, increased the cyclic fatigue life of 94-percent alumina-ceramic cylinders significantly. The 12-inch-diameter cylinder 1, equipped with Mod 1 end caps, successfully withstood 500 cycles to 9,000-psi design depth without visible exterior spalling. Because of the significant improvement in cyclic fatigue life

provided by Mod 1 end caps, all joints in the 12-inch ceramic housings were redesigned to incorporate the Mod 1 end caps (figures 37 and 38).

When pressure tested to destruction with ends radially supported by plane steel bulkheads, ceramic cylinder 1 imploded at 16,500 psi. Since the implosion pressure of this cylinder differs little from critical pressures generated in phase 1 of this program by 6-inch-diameter cylinders with identical t/D_0 and L/D_0 ratios, it can be concluded that the extent and depth of fatigue cracks in the cylinder with Mod 1 end caps after 500 cycles to design depth were not large enough to reduce the structural performance of the cylinder significantly.

Nondestructive Evaluation of Ceramic Components

1. The *presence of voids* with diameters ≥ 0.010 of an inch can be detected in ceramic shells with a thickness of 0.412 inch by using either the ultrasonic pulse-echo, or through-transmission data-acquisition methods. To achieve such fine resolution, the C-scan of the ceramic cylinder or hemisphere must be performed at 0.01-inch increments using a 10 MHz frequency.
2. The *location of a void* can be accurately pinpointed in the X-Y plane by through-transmission, or pulse-echo methods operating in C-scan mode, and its distance from the surface of the shell can be pinpointed by pulse-echo method operating in A-scan mode.
3. The *size of the void* cannot be accurately determined by sonic inspection methods as the magnitude of signal generated by echo from the void depends not only on its size, but on its shape. As a rule, the image of a void detected by an ultrasonic C-scan is 100- to 200-percent larger than the void itself.
4. The *size of a void* can be accurately determined by X-ray inspection techniques. The most sensitive method is digital X-ray computed tomography, followed by digital radiography and film X-ray. The width of the void, or separation of fracture surfaces at right angles to the ray path, must be ≥ 3 percent of the ceramic shell thickness in order to be detectable by X-ray inspection techniques.
5. The *location of a void* can be located in the X-Y plane by all three X-ray inspection methods. Its location with respect to the shell surface can be established accurately *only* by radiographic computed tomography.
6. The *three-dimensional shape* of the void as well as its location inside the ceramic shell can be accurately determined only by radiographic computed tomography (figure 39). Because of the high cost, it must be applied only to locations where ultrasonic inspection has previously pinpointed the presence of a large void.
7. The magnitude of voids detected in the 6- and 12-inch-diameter housings and hemispheres varied in size from 0.01 to 0.05 inch. The number of voids varied from one cylinder to another. The largest number of voids was found in cylinder 3 at an apparent density of three voids per cubic inch. Over 90 percent of the voids detected were ≤ 0.015 inch in size. The sizes of voids in the remaining 10 percent of void population varied from 0.015 to 0.050 inch.
8. Some voids in the 0.04- to 0.05-inch range were found within 0.05 inch of the external surface. They did not implode, or serve as crack initiators when the external surface of the cylinder was subjected to 10,000-psi proof pressure.
9. Voids with diameters ≤ 0.05 of an inch do not initiate cracks in ceramic cylinders pressurized externally to $\leq 300{,}000$-psi compressive stress level.

CONCLUSIONS

1. Ceramic of 94-percent Al_2O_3 composition is a reliable material for construction of external pressure housings designed to operate at compressive stress levels of ≤150,000 psi.
2. The 94-percent alumina-ceramic housings can tolerate voids with ≤0.050-inch-diameters under compressive stress loading of –300,000 psi magnitude during a single pressurization, and –150,000 psi during multiple pressurizations without initiation of cracks.
3. Monocoque cylinders with $t/D_0 = 0.034$ and $L/Do = 1.5$, when supported radially at the ends by ceramic hemispheres, fail by buckling at ≥13,500 psi and at ≥16,500 psi when supported by plane bulkheads.
4. There appears to be no reduction in structural performance of ceramic cylinders and hemispheres under external pressure associated with linear scaling up of their dimensions.
5. Ceramic, instead of titanium, hemispheres can be used as end closures in ceramic cylindrical housings.
6. Multiple penetrations can be incorporated into a ceramic hemisphere without reducing its critical pressure.
7. Ceramic cylinders and hemispheres can be joined and securely fastened with mechanical joints of split wedge bands that draw titanium end cap rings (bonded with epoxy adhesive) to the ends of the cylinders and hemispheres.
8. The cylindrical housing assemblies can be extended to any length by joining and fastening many cylindrical sections together. To prevent reduction of elastic stability resulting from the increase in spacing between radial supports provided by hemispherical end closures, stiffeners must be incorporated into the cylindrical housing assembly. Stiffeners may be incorporated into the joints between ceramic cylinders or inserted inside the cylinder and bonded to its interior surface.
9. Metallic ring stiffeners, when incorporated into joints between cylindrical housing sections, replace the radial support to the end of a cylinder that was previously supported by a hemisphere.
10. Metallic ring stiffeners, bonded to the interior surface of a monocoque ceramic cylinder at midbay or at lesser intervals, make it feasible to reduce the shell thickness or increase the cylinder length without reducing its elastic stability.
11. The cyclic fatigue life of ceramic components in the pressure housing is determined by the growth rate of axial cracks on the plane-bearing surfaces initiated by tensile radial stresses at that location.
12. Tensile radial stresses are generated by the mismatch in the physical properties of the ceramic shell and the adhesive-bonded titanium end cap. The magnitude of tensile radial stress is inversely related to the modulus of elasticity of the material from which the end cap is fabricated (i.e., an aluminum end cap generates higher tensile radial stress on the ceramic bearing surface than an end cap made from titanium).
13. The cyclic fatigue life of plane-ceramic bearing surfaces under repeated –70,000 psi axial loadings has been found to be >100 pressure cycles when encapsulated in Mod 0, and >500 pressure cycles when encapsulated in Mod 1 end caps.
14. A W/D ratio of 0.6 is achieved by housings of a *single* 94-percent alumina-ceramic monocoque cylinder with $t/D_0 = 0.034$ and $L/Do = 1.5$ equipped at the ends with Mod 1 titanium end caps, and closed off by ceramic hemispheres with Mod 1 end rings.
15. Voids in 0.412-inch-thick ceramic shells can be detected by several nondestructive techniques. *Ultrasonic technique* detects voids ≥0.01 inch, *digital radiographic tomography* detects voids ≥0.02 inch, and *digital radiography* or *film X-ray technique* detects voids ≥0.03 inch.

16. The size of the void can be accurately measured only by digital radiographic tomography. Digital radiography and X-ray film techniques produce close approximations of the actual size, with the images of the voids slightly (approximately 1 to 3 percent) oversize. Ultrasonic microscopy presents images that are approximately 5- to 10-percent larger than voids. Standard ultrasonic C-scans generate images that are 100- to 200-percent larger than voids and, for this reason, are not suited for measuring void sizes.

RECOMMENDATIONS

1. The cost-effective *design* for ceramic external pressure housings consists of a monocoque cylinder and two hemispheres whose ends, after encapsulation in titanium end caps, are fastened together by split wedge bands. The payload capacity of such a housing may be increased economically by joining several identical cylindrical sections with joint ring stiffeners that not only line up, but also provide radial support to the ends of the cylinders.

2. The compressive design stress in any of the ceramic components fabricated from 94-percent alumina should not exceed –150,000 psi, except at penetrations in the ceramic hemispheres where a local compressive stress of –200,000 psi magnitude is acceptable.

3. To maximize the cyclic fatigue life of the axial bearing surfaces on ceramic cylinders and hemispheres, their ends must be protected by titanium end caps of Mod 1 design filled with epoxy adhesive (figures 41 and 42). The height of the flanges on the end cap must meet the $h = 3.2\ t_c$ requirement. An epoxy layer ≤ 0.01-inch thick is the preferred interface between the mating ceramic and titanium bearing surfaces inside the end cap.

4. With Mod 1 end caps the cyclic fatigue life of bearing surfaces on 94-percent alumina ceramic housing components subjected to –68,000 psi average bearing stress exceeds 500 cycles to design pressure.

5. To reduce the axial bearing stress on the edge of the ceramic hemispherical bulkhead to the same level as on the adjoining ceramic cylinder, the shape of the equatorial edge on the hemisphere should be modified to represent a cylindrical skirt with the same thickness as the mating cylinder.

6. To attain a 50-percent margin of safety against material failure and elastic buckling at design pressure of 9,000 psi, the 94-percent alumina-ceramic monocoque cylinder must have $t/D_o = 0.034$ and $L/D_o = 1.5$ dimensions.

7. To provide the ceramic components with adequate impact protection, an elastomeric jacket 0.25-inch thick should be placed over the ceramic surfaces.

8. All ceramic components must be nondestructively inspected for external cracks and internal defects in the form of voids or cracks. Components with external or internal cracks of any length are not acceptable. Voids > 0.05 inch also make the component unacceptable unless empirical data can be found to the contrary.

9. The following cost-effective nondestructive QC inspection procedure is recommended for ceramic components:

   a. Apply dye penetrant to all surfaces, and visually inspect for cracks.

   b. Perform continuous ultrasonic C-scan indexed at 0.01-inch intervals of shell surface by means of pulse-echo, or through-transmission techniques utilizing > 10 MHz transducers calibrated on a ceramic witness specimen with 0.03-inch flat bottom hole.

   c. Place film on the interior surface of the ceramic shell at locations where ultrasonic C-scan has located voids that *appear* to exceed 0.05 inch in size, and expose it with X-rays.

   d. Develop the film and measure the images of voids. Use these measurements as the basis for acceptance or rejection of the ceramic component.

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1. Stachiw, J. D. and B. Frame. 1988. "Graphite-Fiber-Reinforced Plastic Hull Mod 2 for the Advanced Unmanned Search System (AUSS)," NOSC TR 1245, (Aug). Naval Ocean Systems Center, San Diego, CA.

2. Stachiw, J. D. 1964. "Solid Glass and Ceramic External Pressure Vessels," External Report No. 63-0209C, Ordnance Research Laboratory, Pennsylvania State University.

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4. Stachiw, J. D. 1968. "Hulls for Deep Submergence Capsules," *American Society Bulletin*, Vol. 47, No. 2, February 7, 1968.

5. Stachiw, J. D. 1984. "Exploratory Beryllia Ceramic Cylindrical Housing for Deep Submergence Service," NOSC TR 951 (Jan). Naval Ocean Systems Center, San Diego, CA.

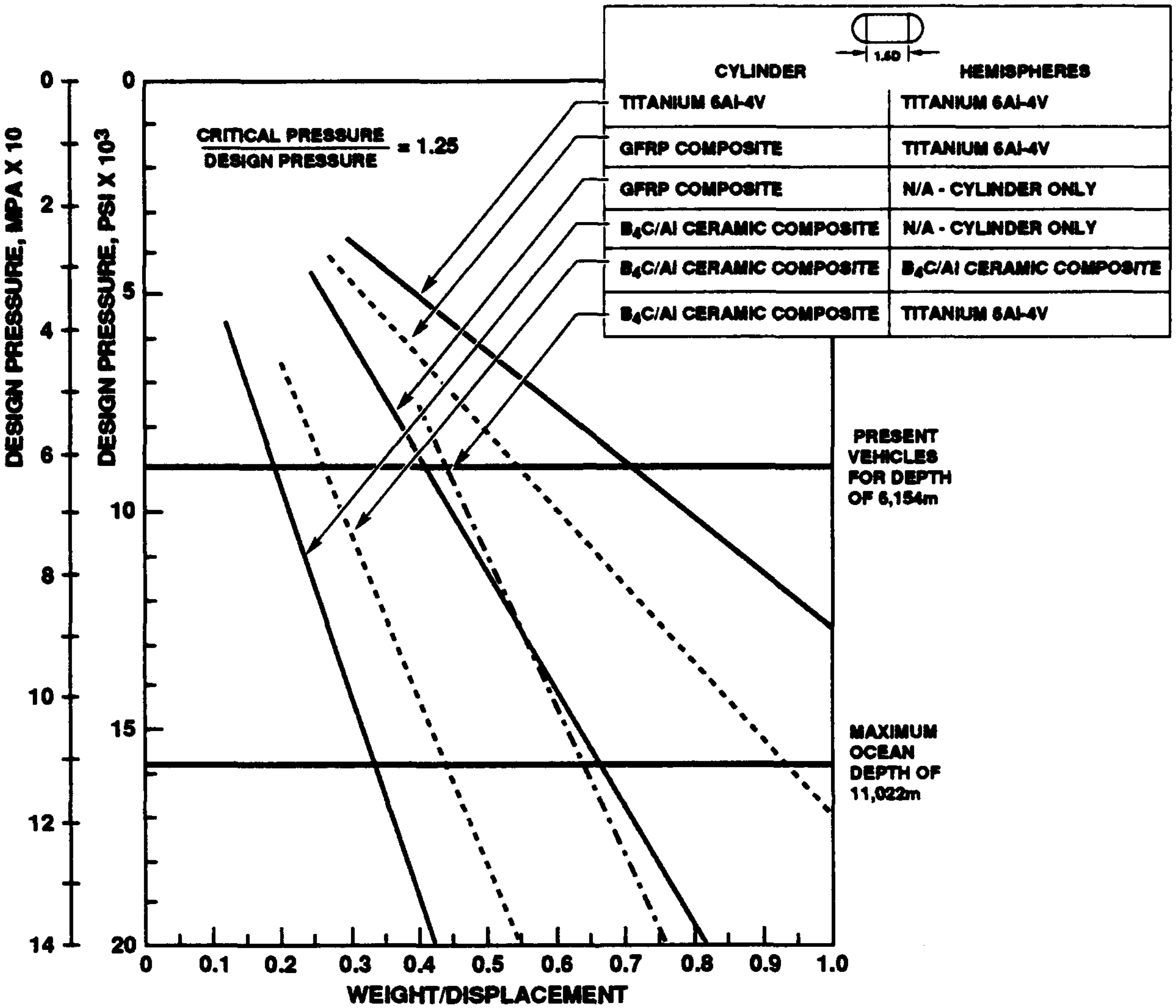
6. Stachiw, J. D. and A. Pyzik, D. Carrol, A. Prunier, T. Allen. 1992. "Boron Carbide Aluminum Cermets for External Pressure Applications," NCCOSC TR 1574 (Sep). Naval Command, Control, and Ocean Surveillance Center RDT & E Division, San Diego, CA.

7. Stachiw, J. D., T. J. Henderson, and C. A. Andersson. 1991. "Novel Ceramic Matrix Composites for Deep Submergence Pressure Vessel Applications," NOSC TD 2222 (Oct). Naval Ocean Systems Center, San Diego, CA.

8. Stachiw, J. D. and J. L. Held. 1987. "Exploratory Evaluation of Alumina Ceramic Cylindrical Housings for Deep Submergence Service: The Second Generation NOSC Ceramic Housings," NOSC TR1176 (Sep). Naval Ocean Systems Center, San Diego, CA.

GLOSSARY

AUV	autonomous underwater vehicle
FEA	finite element analysis
GFRP	graphite fiber-reinforced plastic
h	height of flange on the end cap
ID	internal diameter
IR/IED	Independent Research and Independent Exploratory Development
L	Length
L/D_o	thickness-to-length ratio
NCEL	Naval Civil Engineering Laboratory
NDE	Nondestructive Evaluation
NOSC	Naval Ocean Systems Center
OD	outside diameter
ORL	Ordnance Research Laboratory
ROV	remotely operated vehicle
SF	safety factor (factor of safety)
specific strength	strength-to-density
t	thickness
t_c	thickness of cylinder
t/D_o	thickness-to-diameter ratio
t_s	thickness of sphere
W/D	weight to displacement



	Compressive Strength	Modulus of Elasticity	Density
B_4C/Al Ceramic Composite	400 Kpsi	45,000 Kpsi	0.09 lbs/in^3
Graphite Fiber Reinforced Plastic Composite	82 Kpsi	16,000 Kpsi	0.057 lbs/in^3
Titanium 6Al-4Va Alloy	120 Kpsi	16,500 Kpsi	0.160 lbs/in^3

Figure 1. W/D of external pressure housings fabricated from premium structural materials.

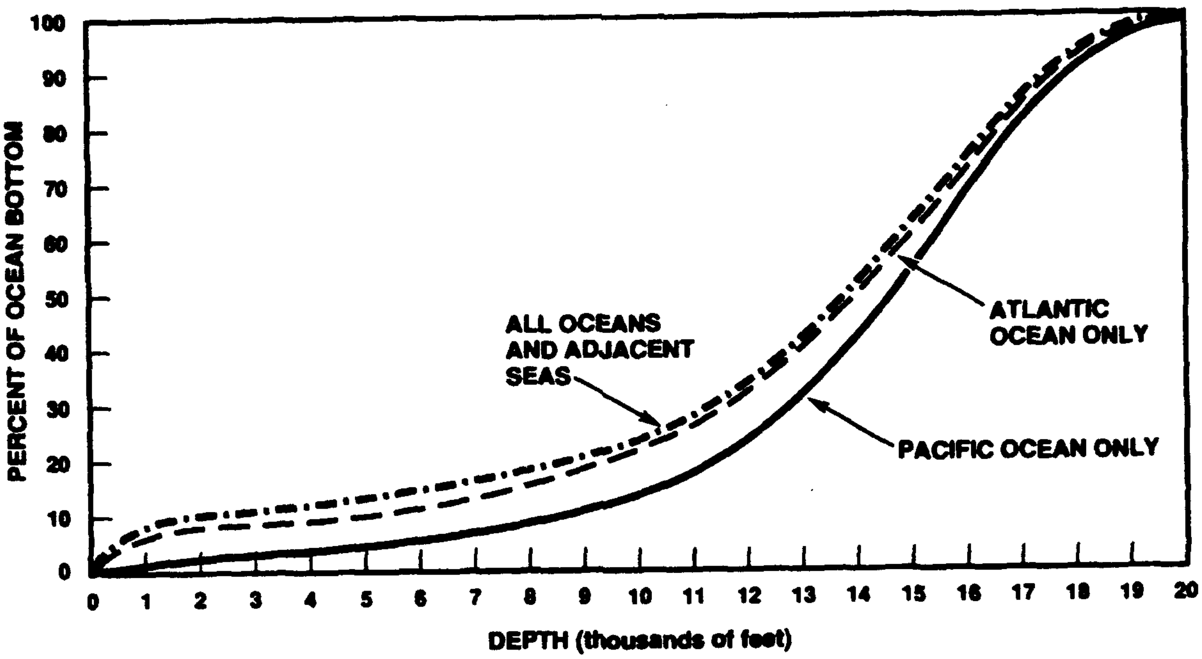


Figure 2. Percent of ocean bottom area within a given depth range.

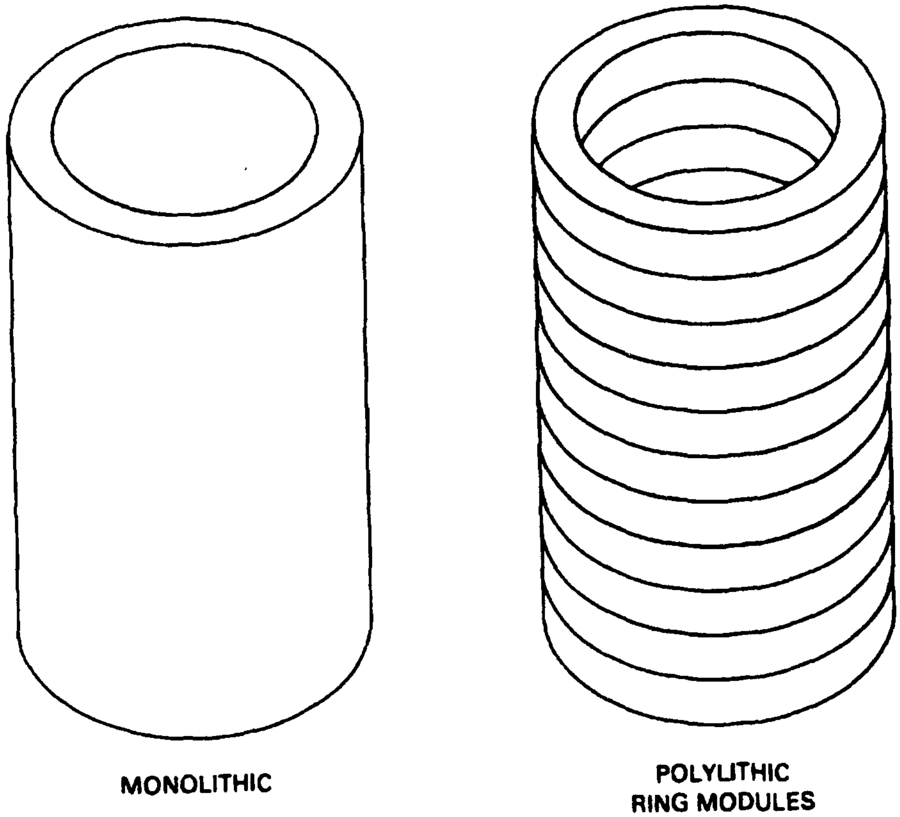


Figure 3. Approaches to construction of monocoque ceramic cylinders.

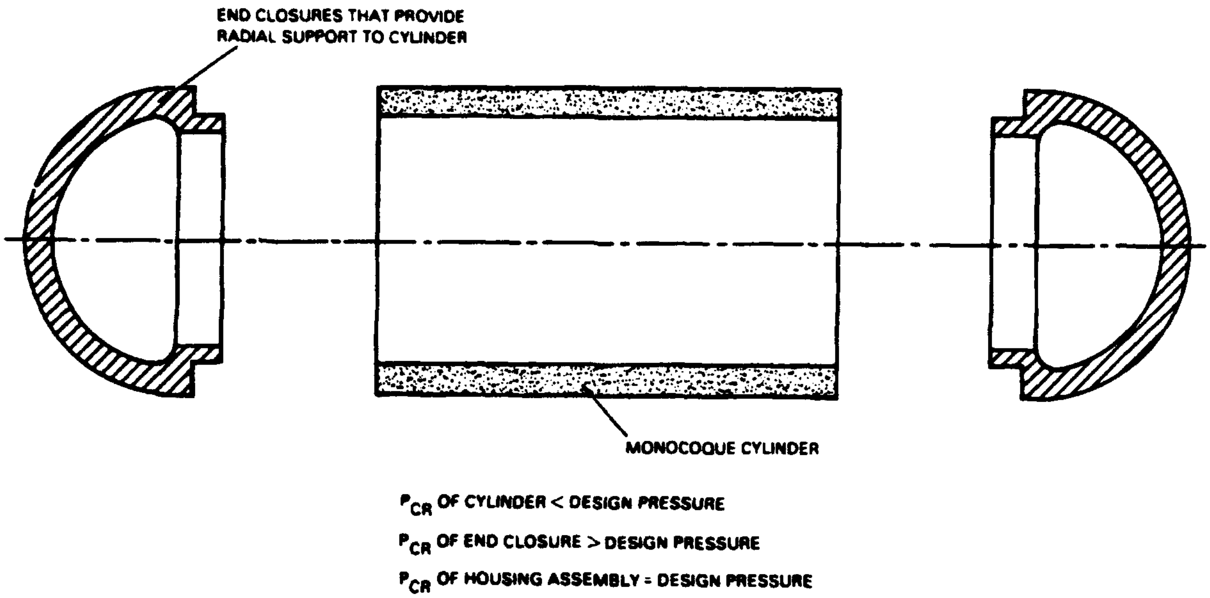
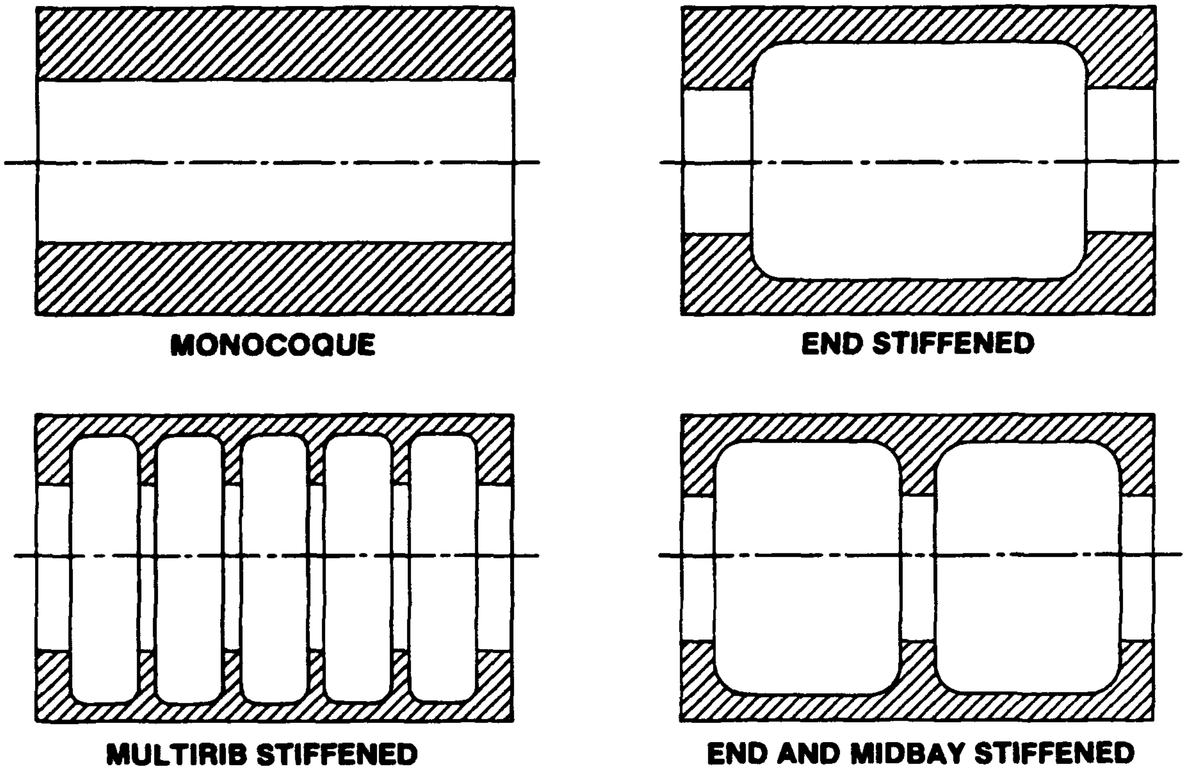


Figure 4. Typical approach to raising the elastic stability of a monocoque cylinder.



Note: All cylinders designed to buckle at the same pressure

Figure 5. Standard techniques for preventing individual cylindrical sections from buckling under external pressure when their ends are not radially supported by bulkheads.

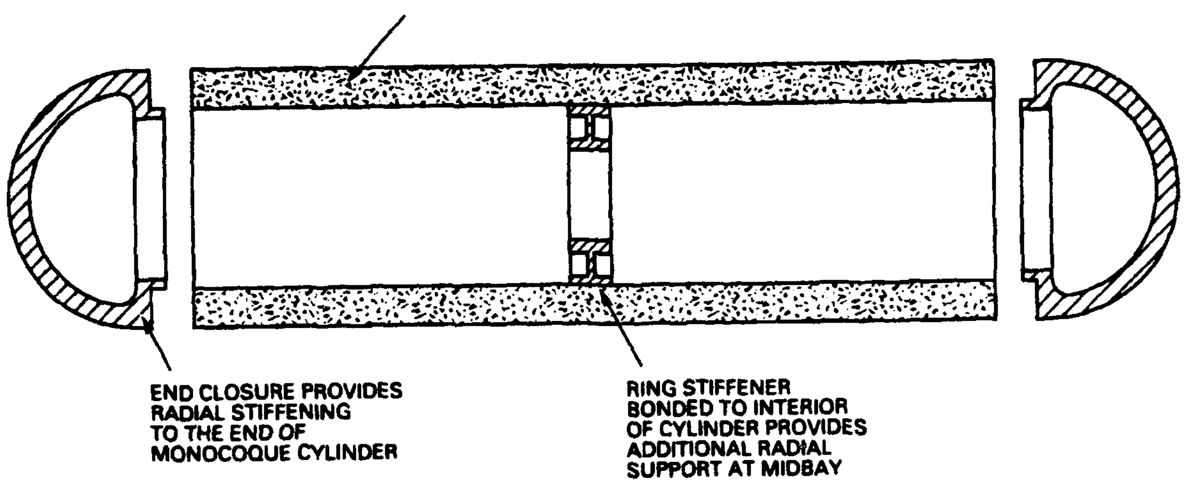


Figure 6. The length of a single monocoque cylinder can be extended without decreasing its critical pressure by inserting one, or more, metallic ring stiffeners into its interior that provide the needed radial support against buckling.

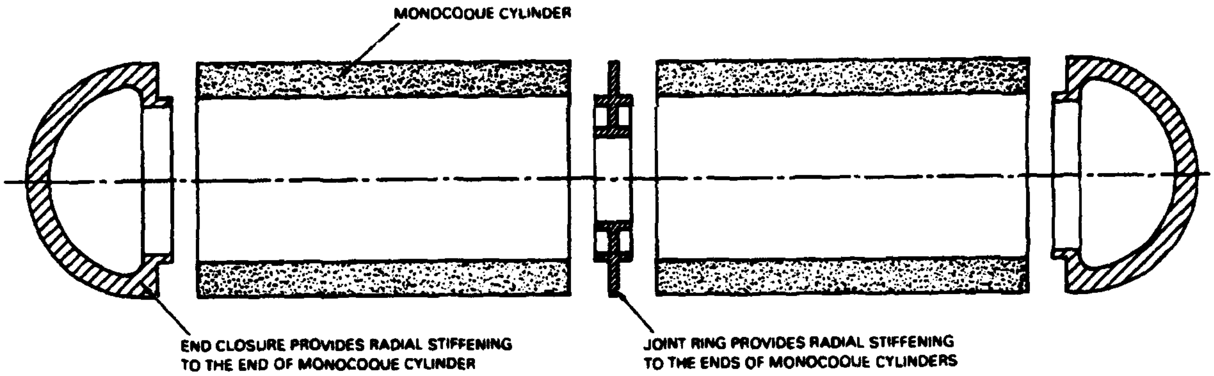


Figure 7. The length of a cylindrical pressure housing assembly can be extended without decreasing its critical pressure by adding more cylindrical sections supported at their ends by metallic joint ring stiffeners.

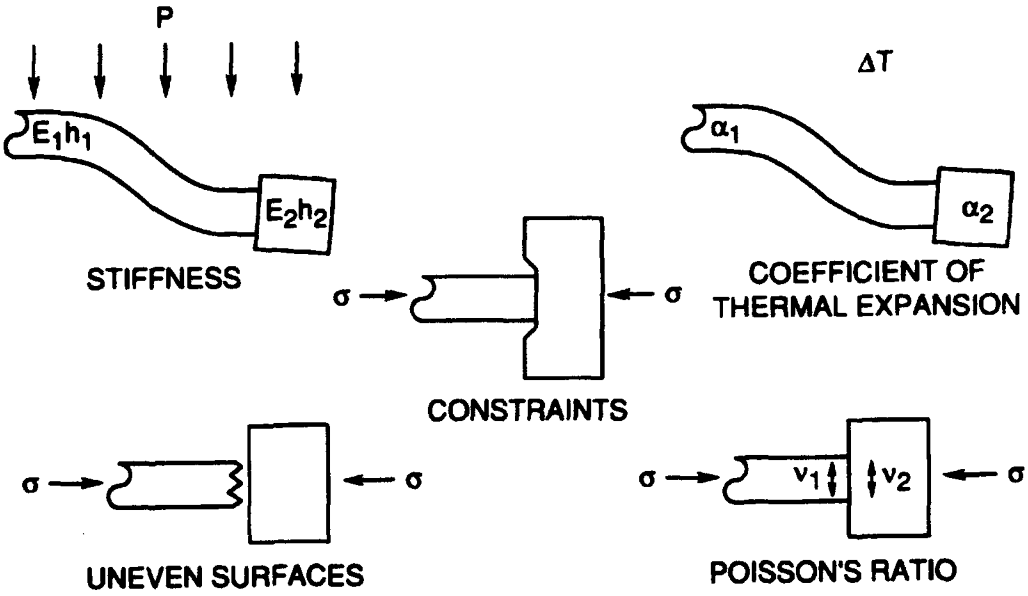


Figure 8. Different types of loadings that affect the magnitude and distribution of stresses in the ceramic components at joints

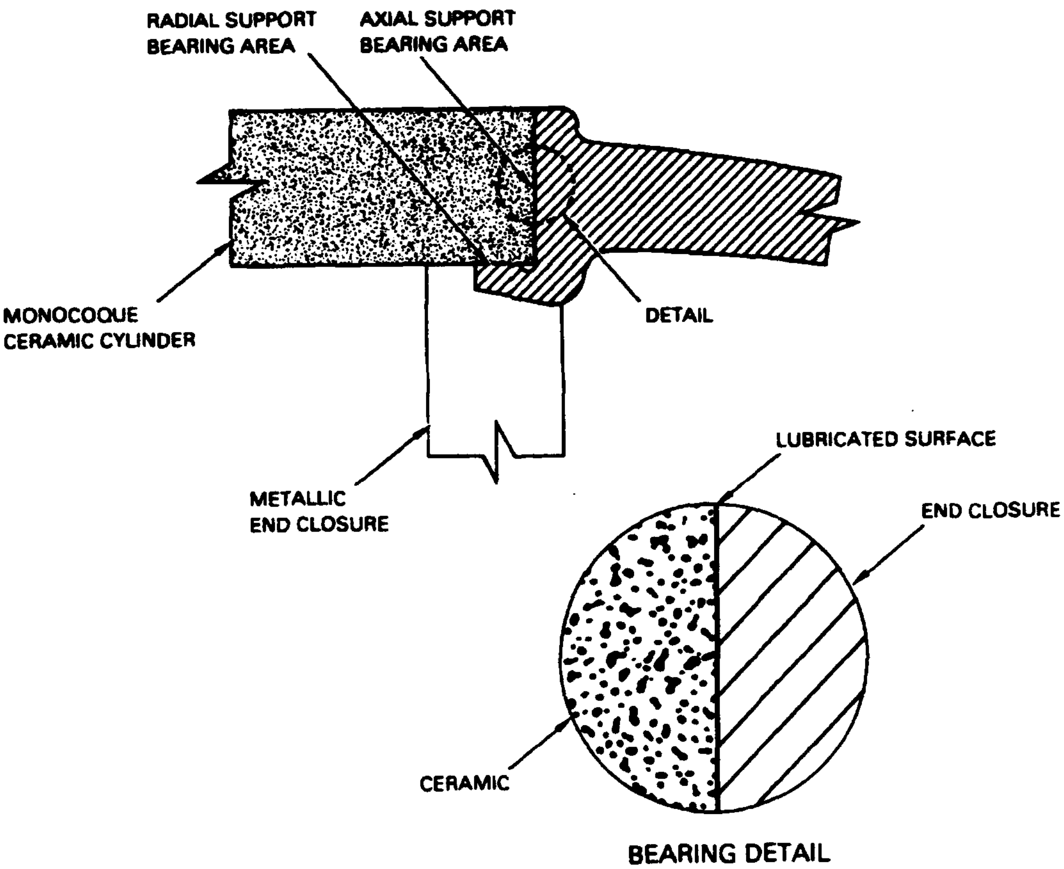


Figure 9. Direct radial and axial support of the ceramic cylinder by metallic bulkheads or joint rings results in fretting of the ceramic bearing surfaces that results in crack initiation, spalling, and, ultimately, failure.

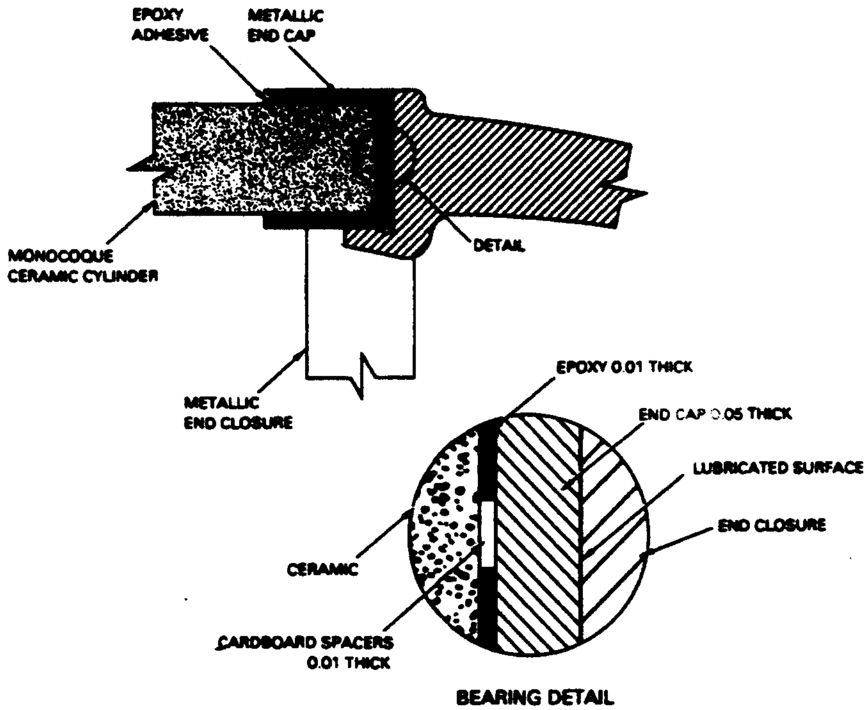


Figure 10. Metallic, circular end caps bonded with epoxy adjesive to the ends of the cylinder protect the ceramic bearing surface from chafing and fretting during repeated pressurizations.

Figure 11. Typical 6-inch-diameter housing consisting of a single ceramic monocoque cylinder protected by end caps and radially supported by titanium bulkheads.

Figure 12. A 6-inch-diameter housing used to demonstrate the feasibility of removable ceramic bulkheads that provide radial support to the cylinder ends by means of a mechanical joint.

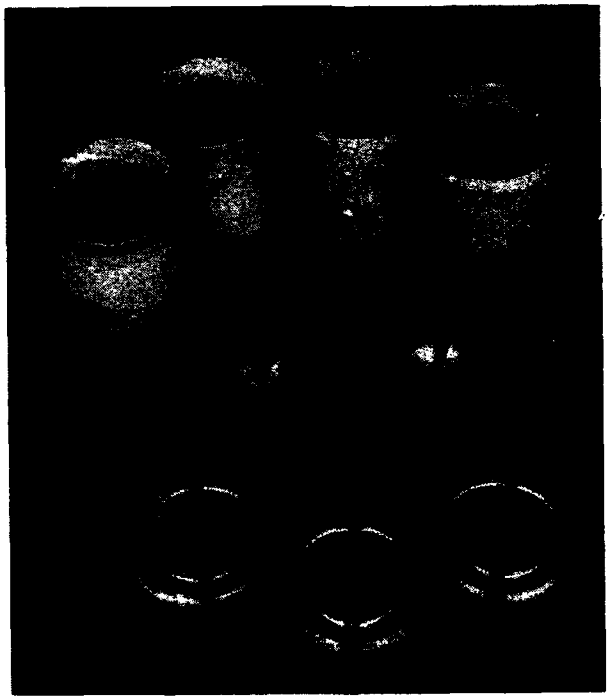


Figure 13. Components of a 6-inch-diameter housing used to demonstrate the feasibility of providing radial support to individual cylindrical sections by means of removable joint ring stiffeners.

Figure 14. A 6-inch-diameter housing assembled from components shown in figure 13 that was subsequently proof tested to 10,000 psi.

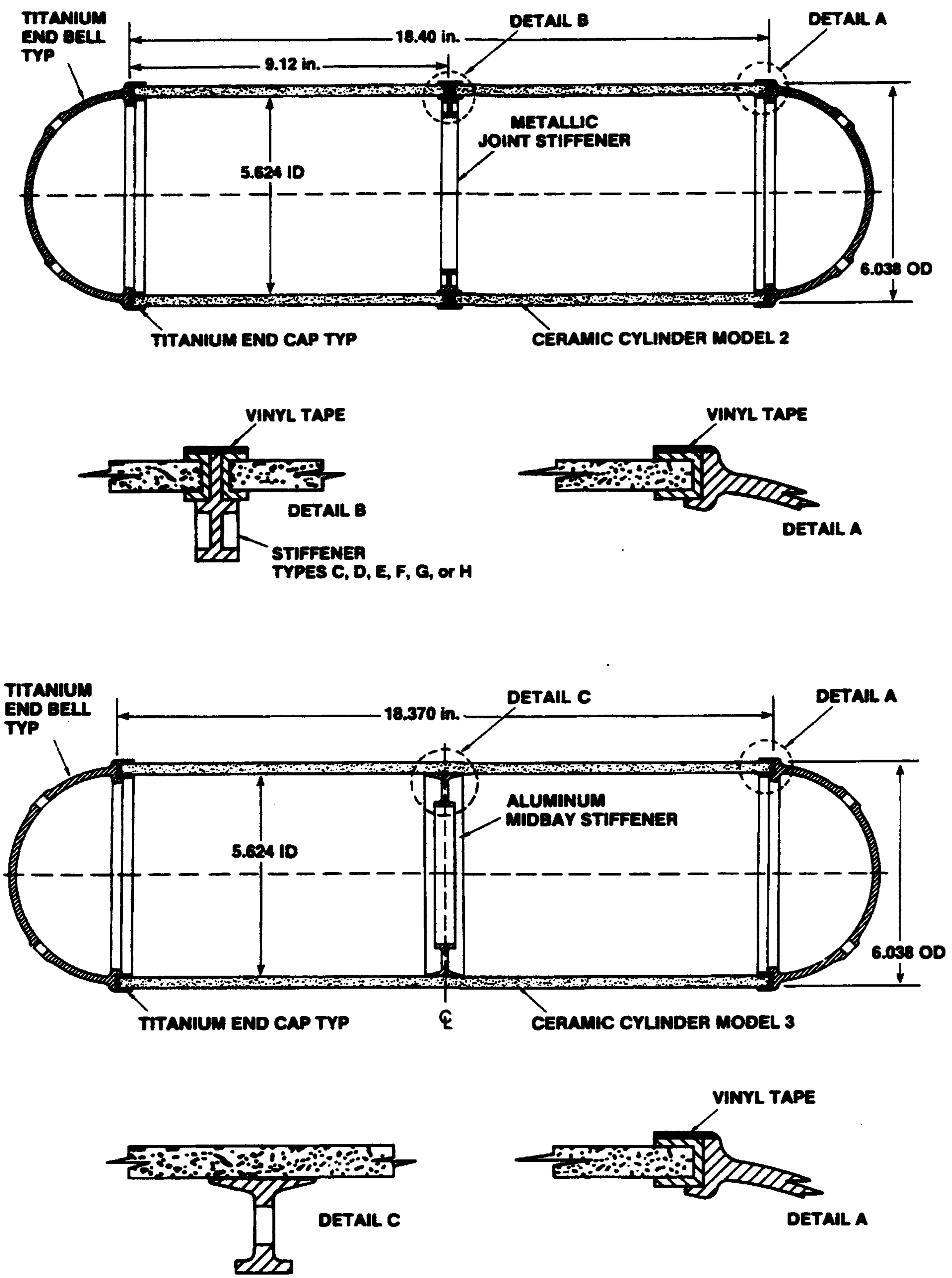


Figure 15. Types of radial support for individual monocoque ceramic cylinders that were incorporated into the 6-inch-diameter NOSC third generation ceramic housings.

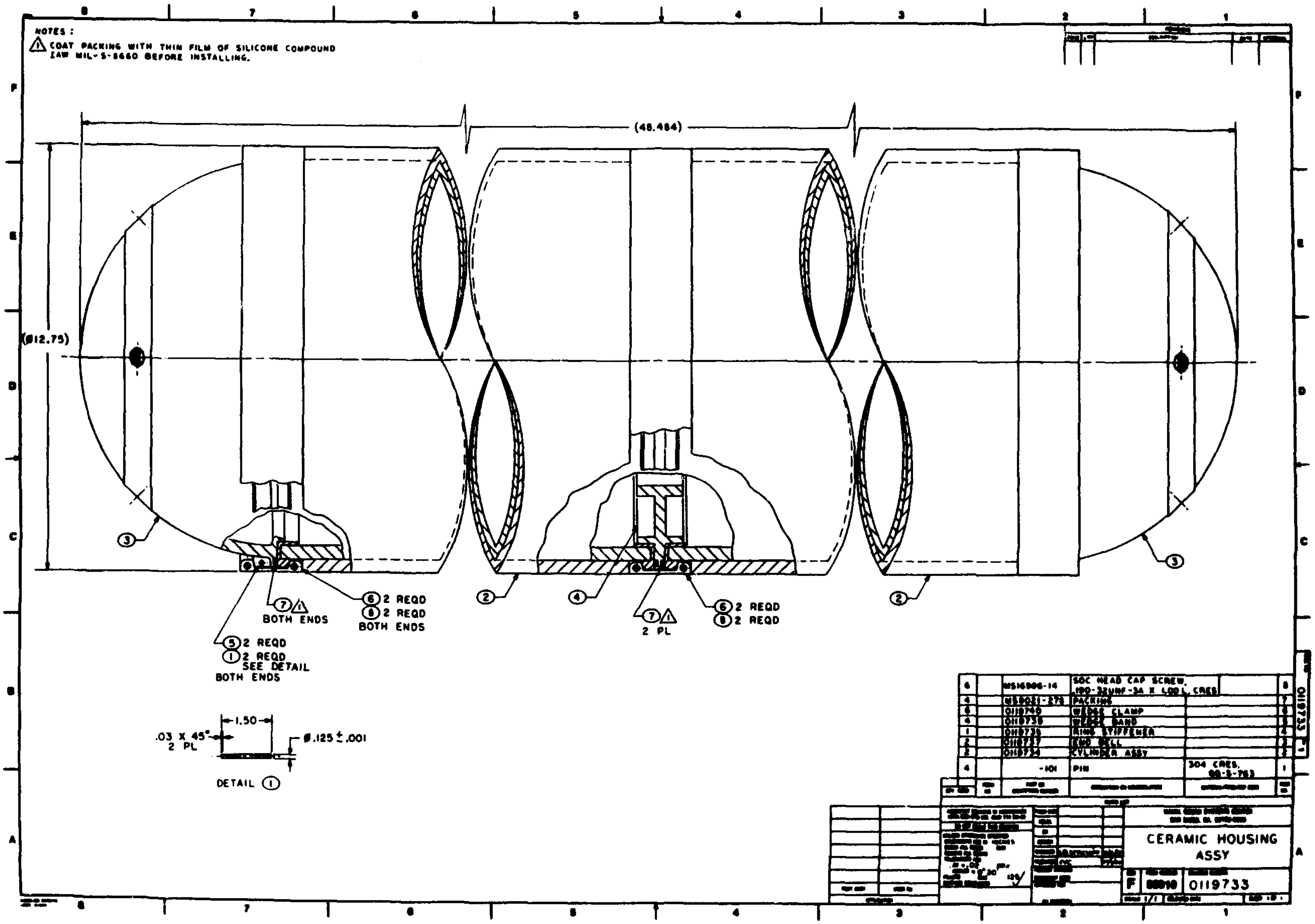


Figure 16. Typical 12-inch-diameter housing used in the evaluation of removable joint ring stiffeners.

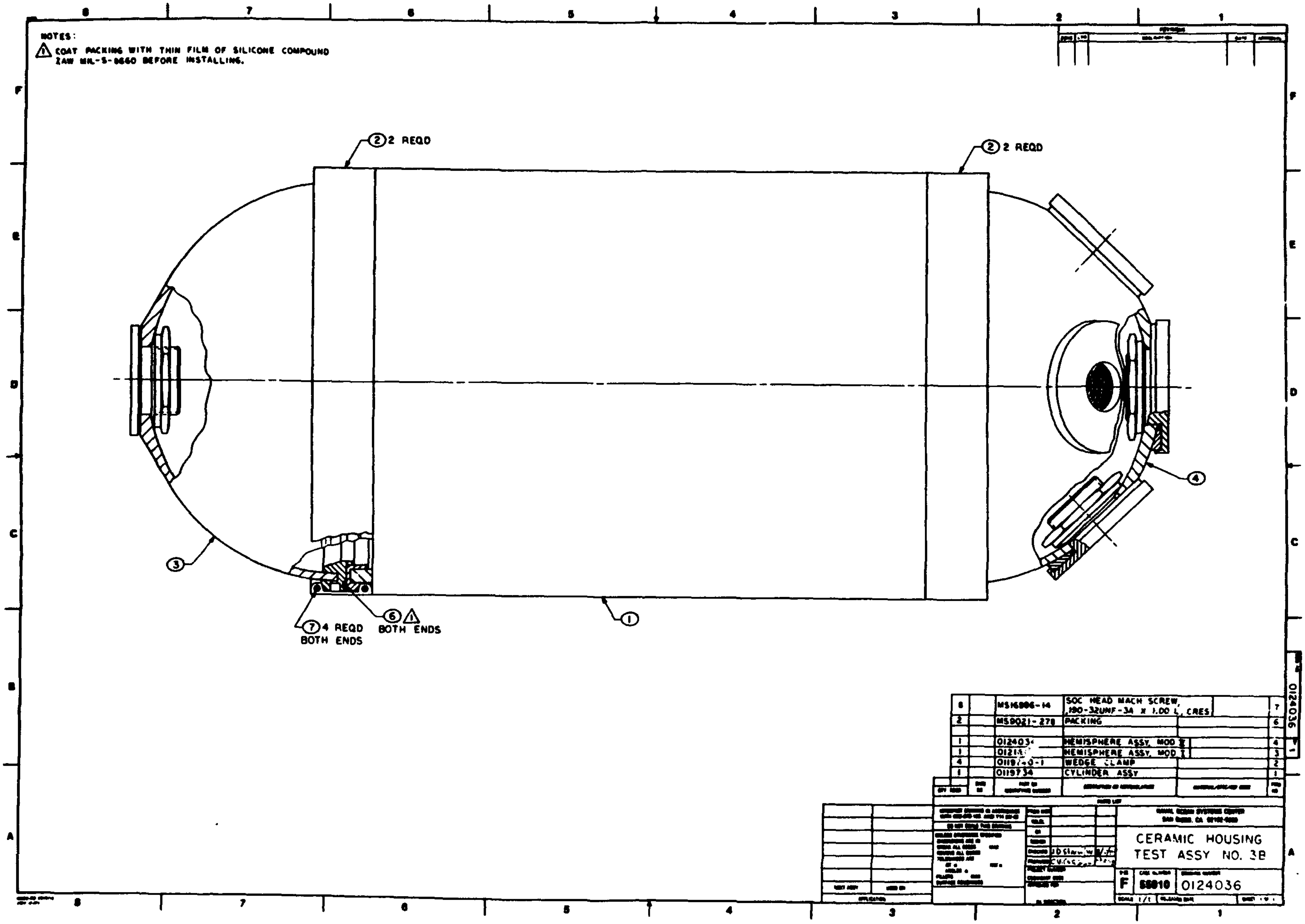


Figure 17. Typical 12-inch-diameter housing used in the evaluation of different ceramic bulkhead configurations.

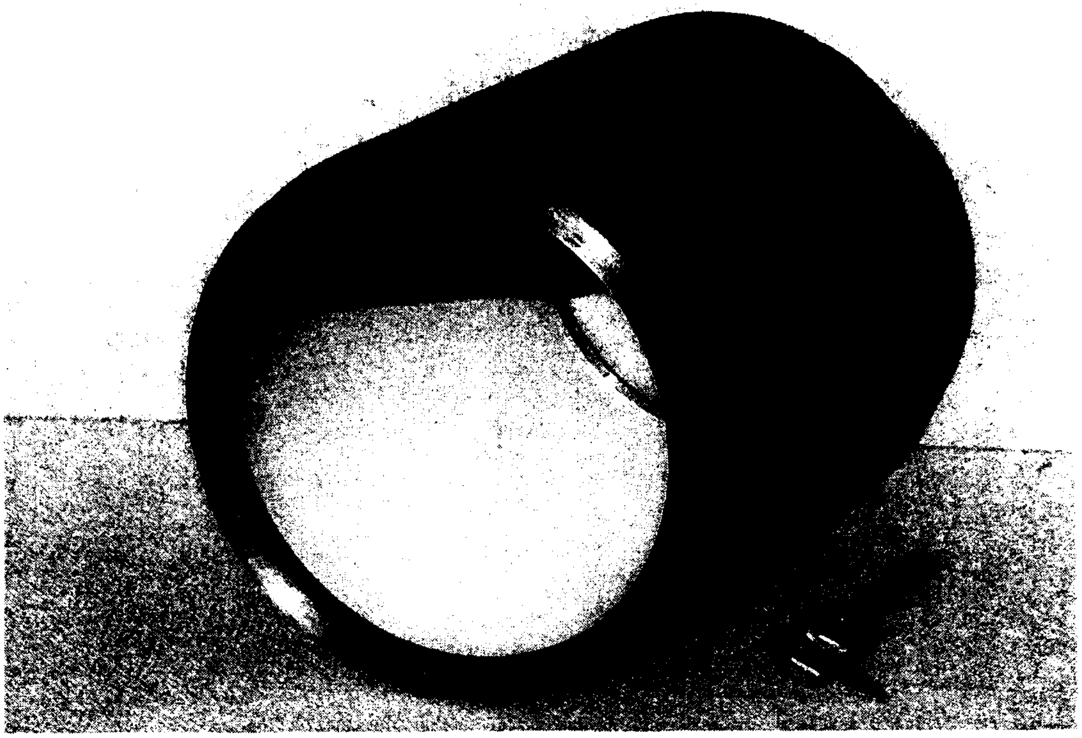


Figure 18. The cylindrical housing section consisting of a 12-inch OD by 18-inch L by 0.412-inch t monocoque 94-percent alumina cylinder equipped with titanium end caps and enclosed by a polyurethane jacket.

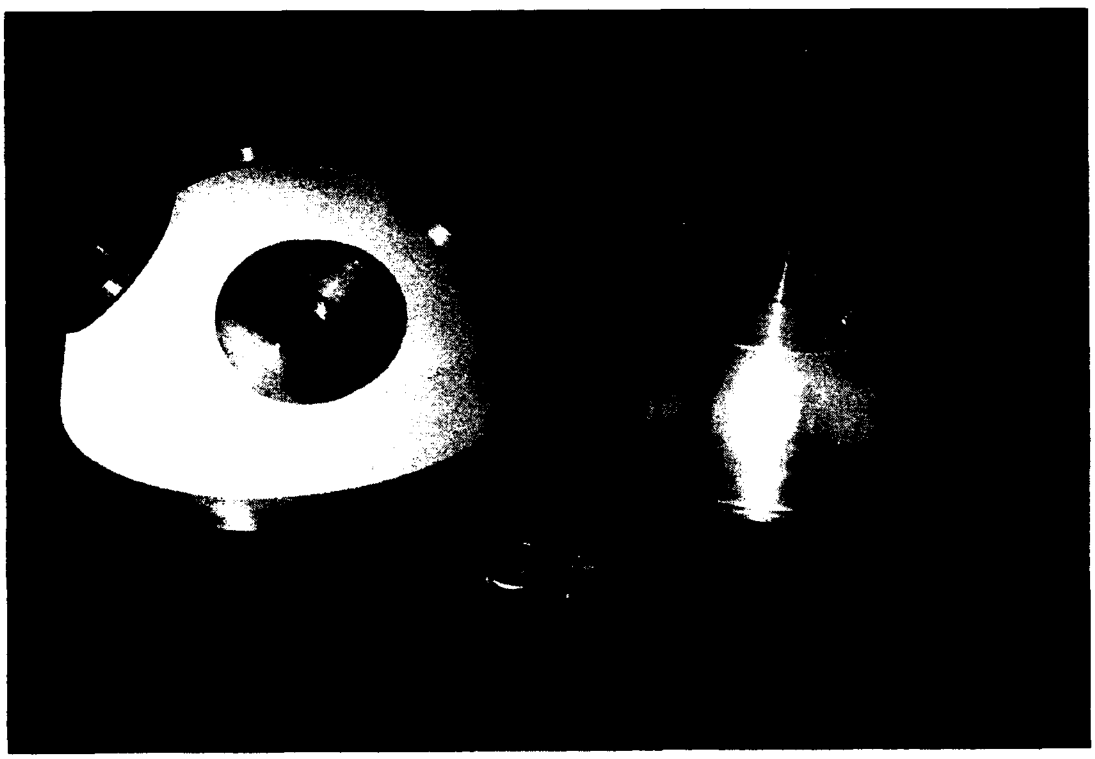


Figure 19. Typical hemispherical bulkheads for the 12-inch-diameter housings.

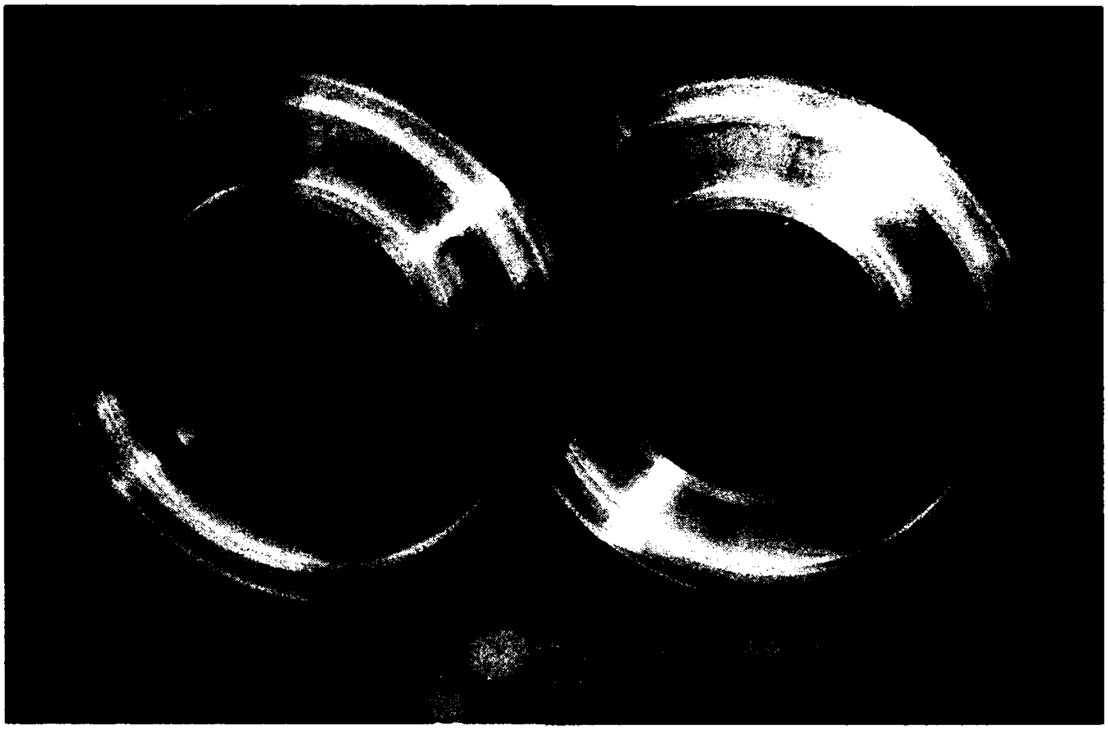


Figure 20. Typical removable joint ring stiffeners for 12-inch-diameter housings.

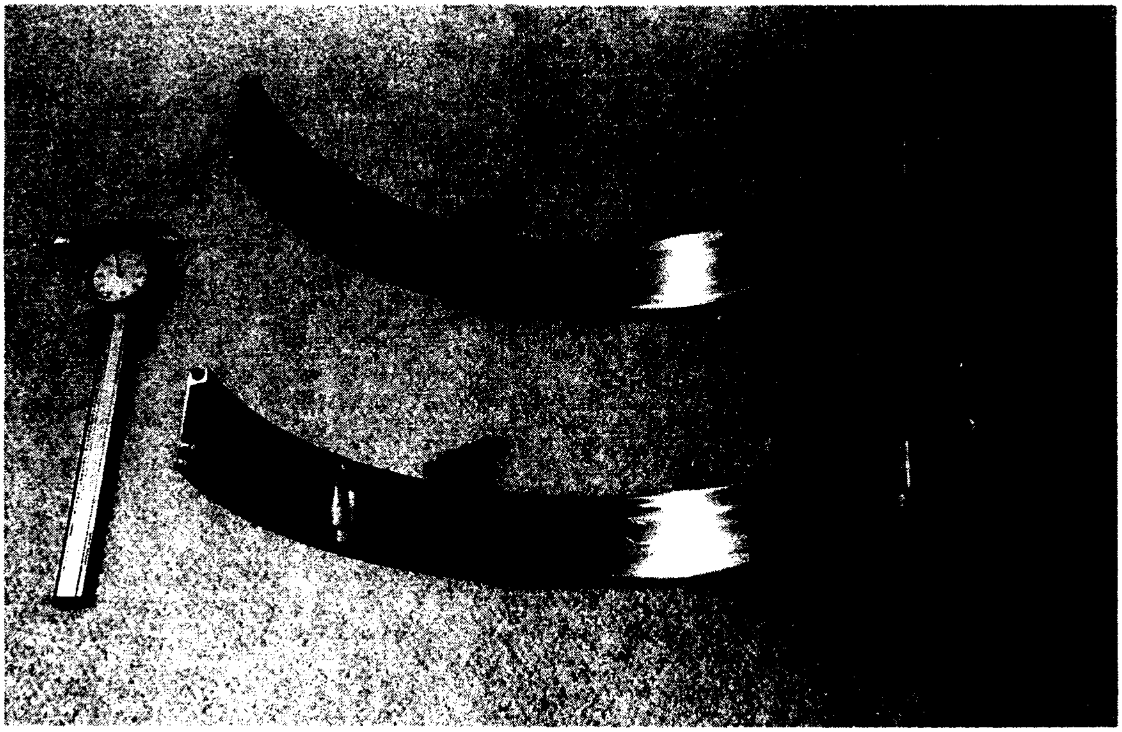


Figure 21. Split wedge bands used for clamping together components of the housing assembly.

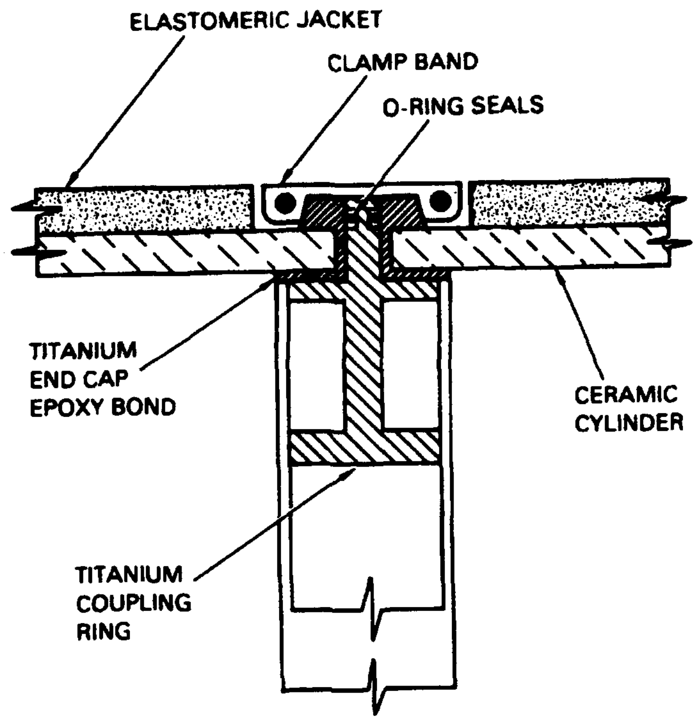


Figure 22. Arrangements for joining ceramic cylinders consisting of Mod 0 end caps, removable joint ring stiffener, and external split wedge band clamp.

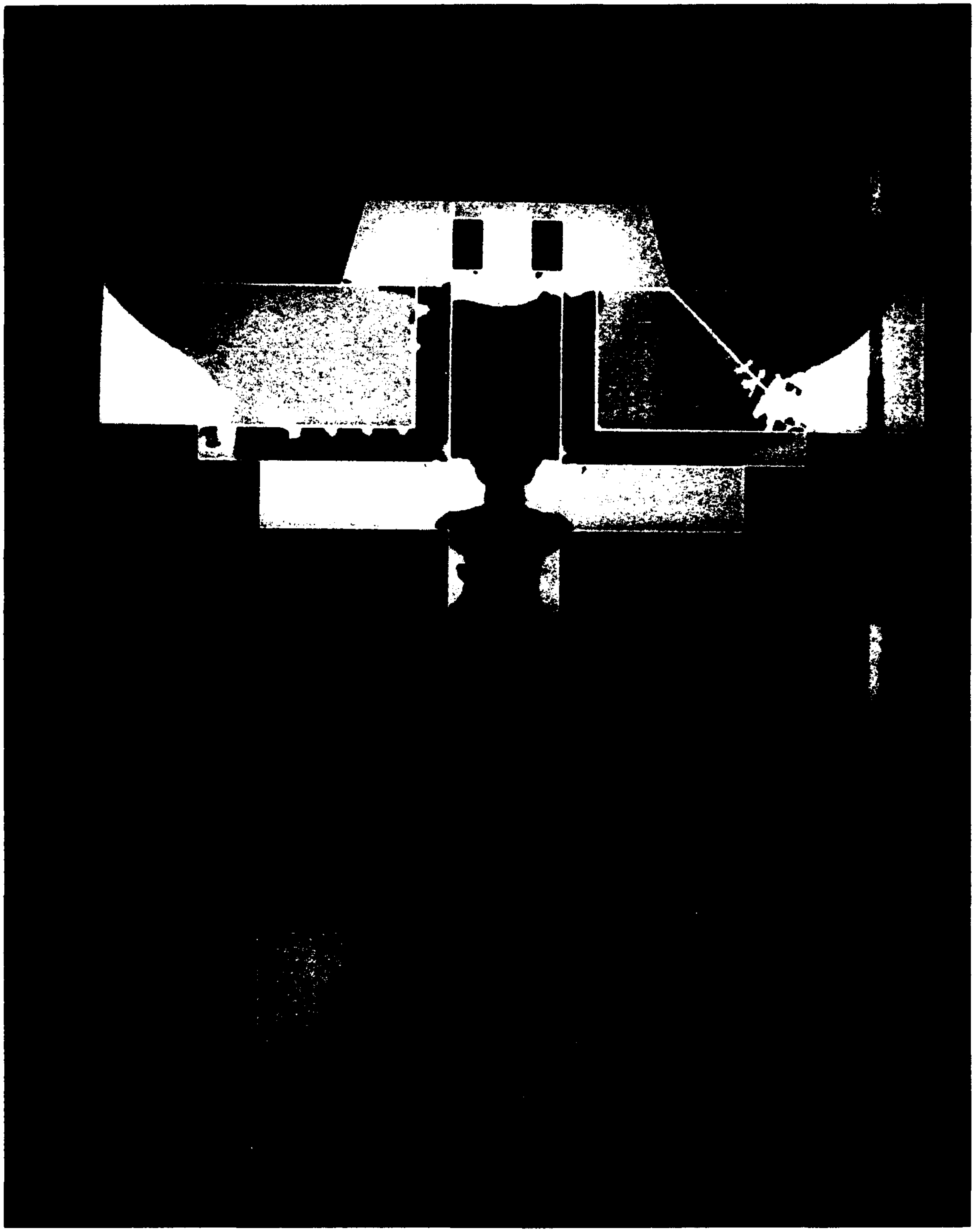


Figure 23. Stress distribution in a typical joint between ceramic cylinders of a 12-inch-diameter housing under 8,900-psi external pressure. The stress shown is minimum principal stress in global frame of reference.

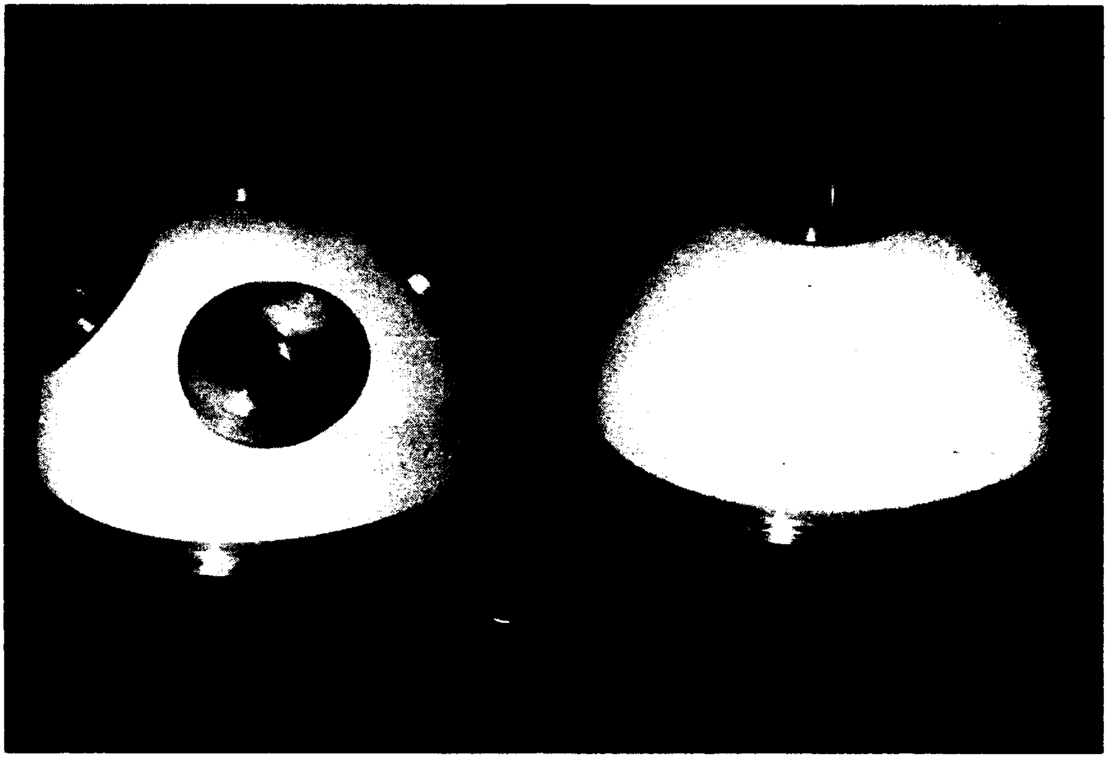


Figure 24. Two of the ceramic bulkhead configurations evaluated in the test program.

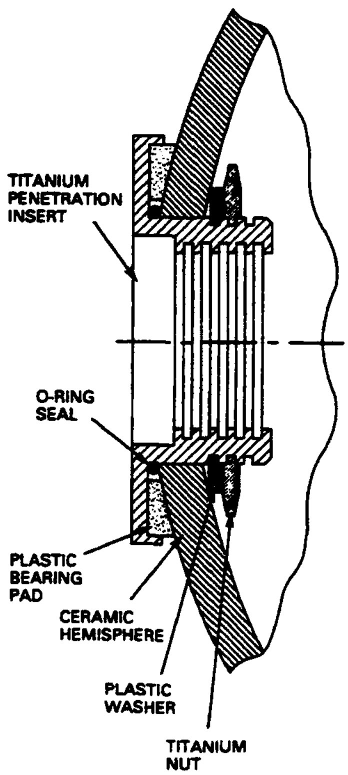


Figure 25. Penetration insert for the ceramic bulkheads that allows screwing in of standard threaded bulkhead penetrators.

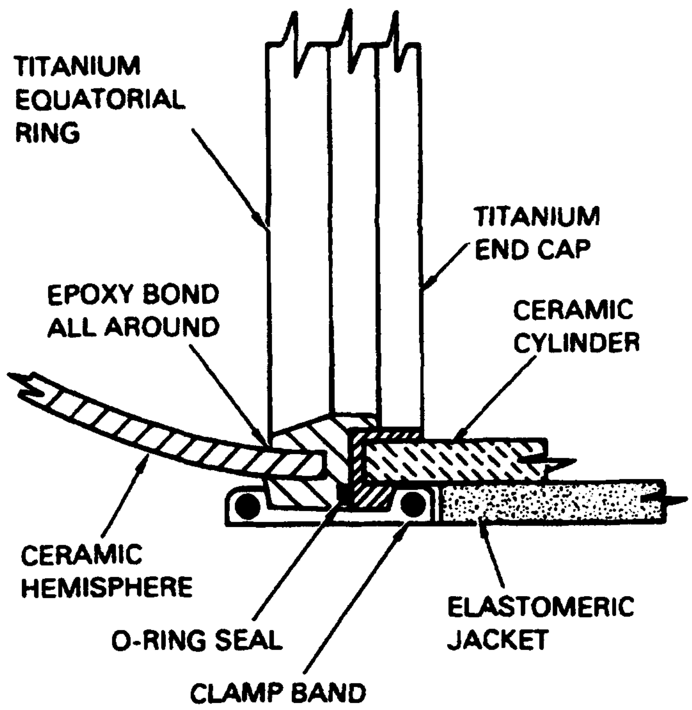


Figure 26. Arrangement for joining ceramic cylinders to ceramic bulkheads using Mod 0 end caps and external split wedge band clamp.

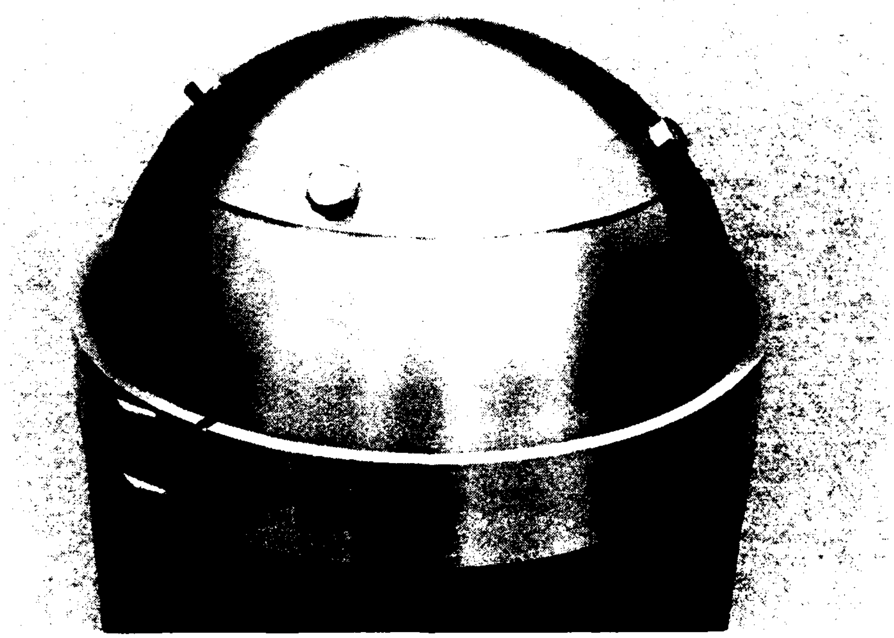


Figure 29. Titanium bulkhead fastened to the 12-inch-diameter ceramic cylinder by means of a split wedge band clamp.

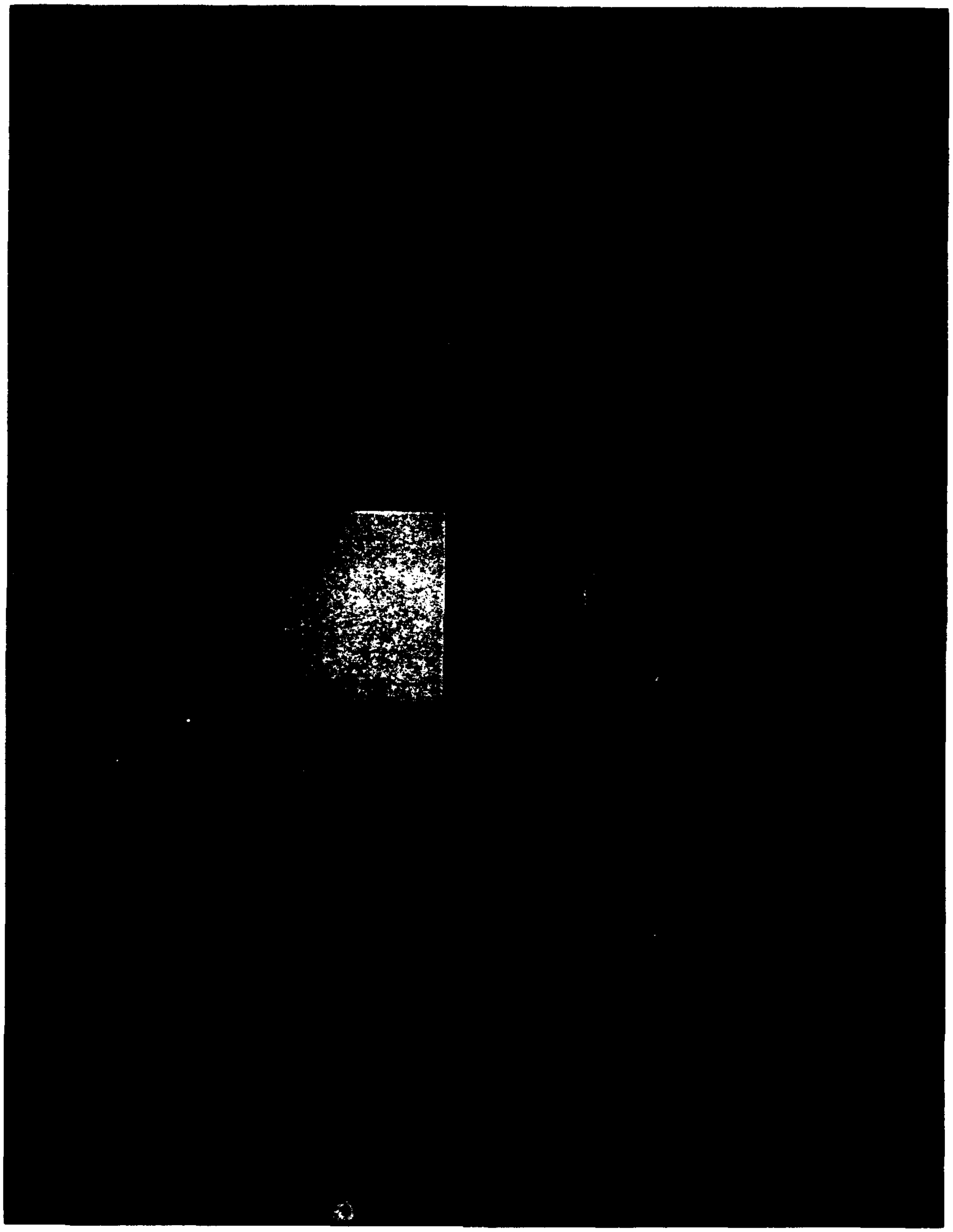


Figure 27. Stress distribution in a typical joint shown in figure 26 between ceramic cylinder and ceramic bulkhead in a 12-inch-diameter housing under 8,9000-psi external pressure. The stress shown is minimum principal stress in global frame of reference.

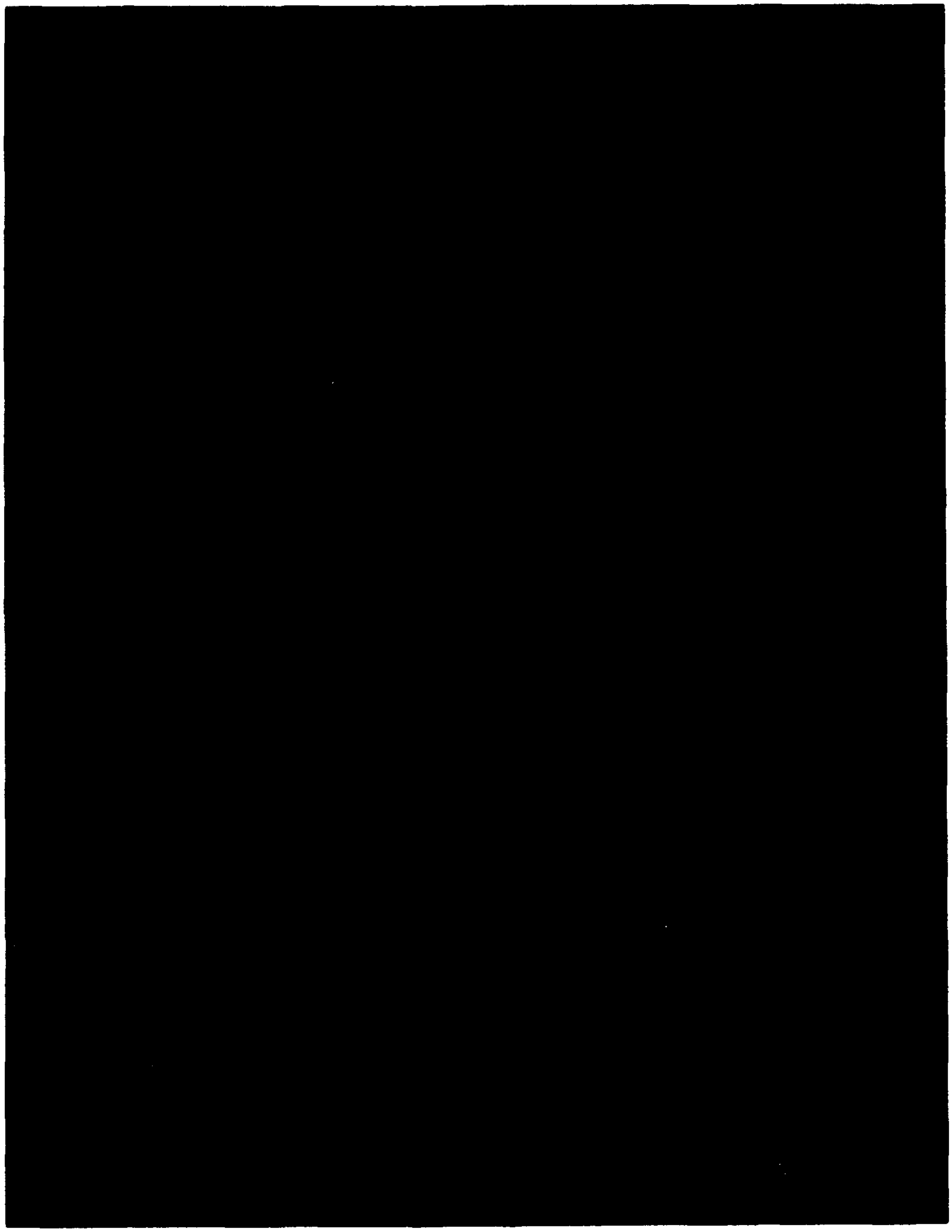


Figure 28. Stress distribution in a typical joint shown in figure 26 between ceramic cylinder and bulkhead under 8,900-psi external pressure. The stress shown is minimum principal stress in axial orientation.

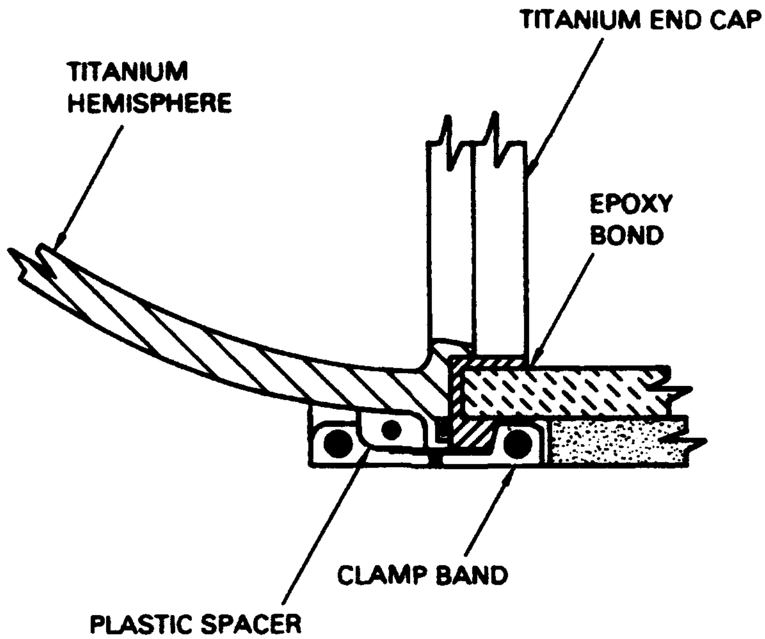


Figure 30. Arrangement for joining a metallic spherical bulkhead to ceramic cylinder using Mod 0 end cap and split wedge band clamp.

Figure 31. Spalling of external surface on 12-inch-diameter ceramic cylinder observed after repeated pressure cycling to 9,000 psi.

Figure 32. Typical fatigue crack on the plane-bearing surface of a ceramic housing component. With continued pressure cycling, the crack will propagate axially and circumferentially.

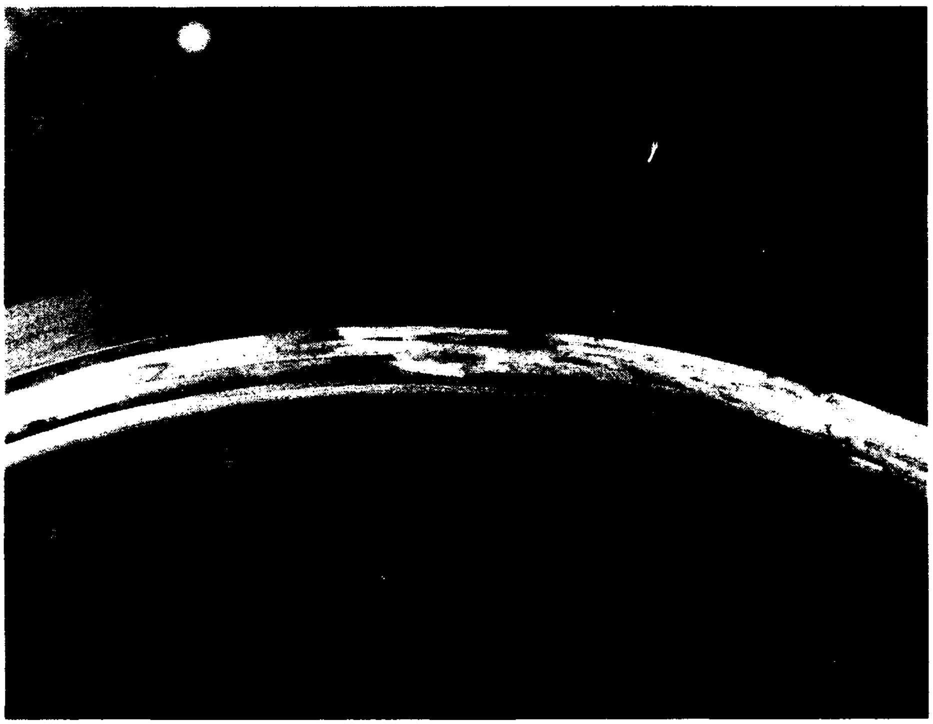
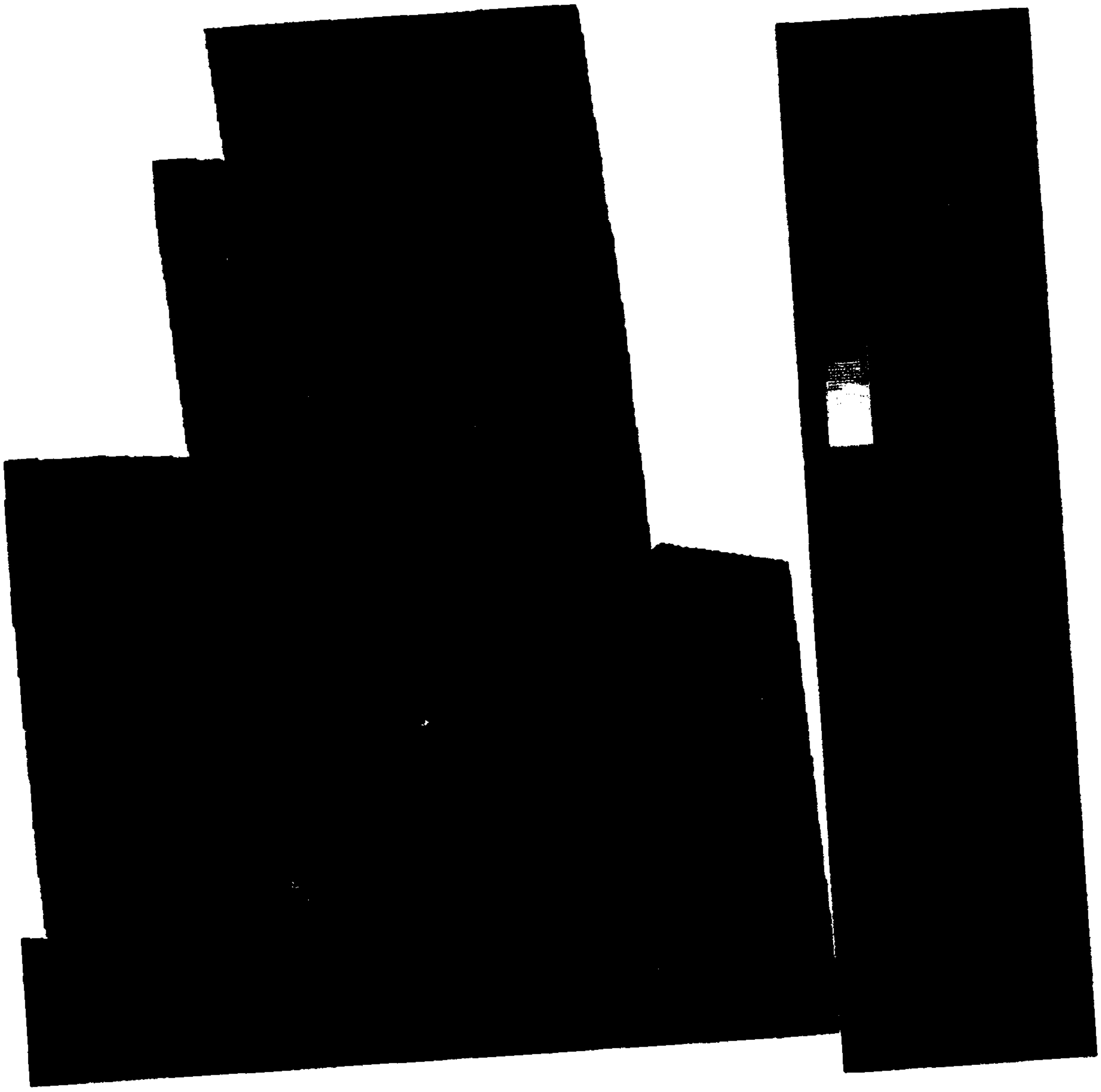
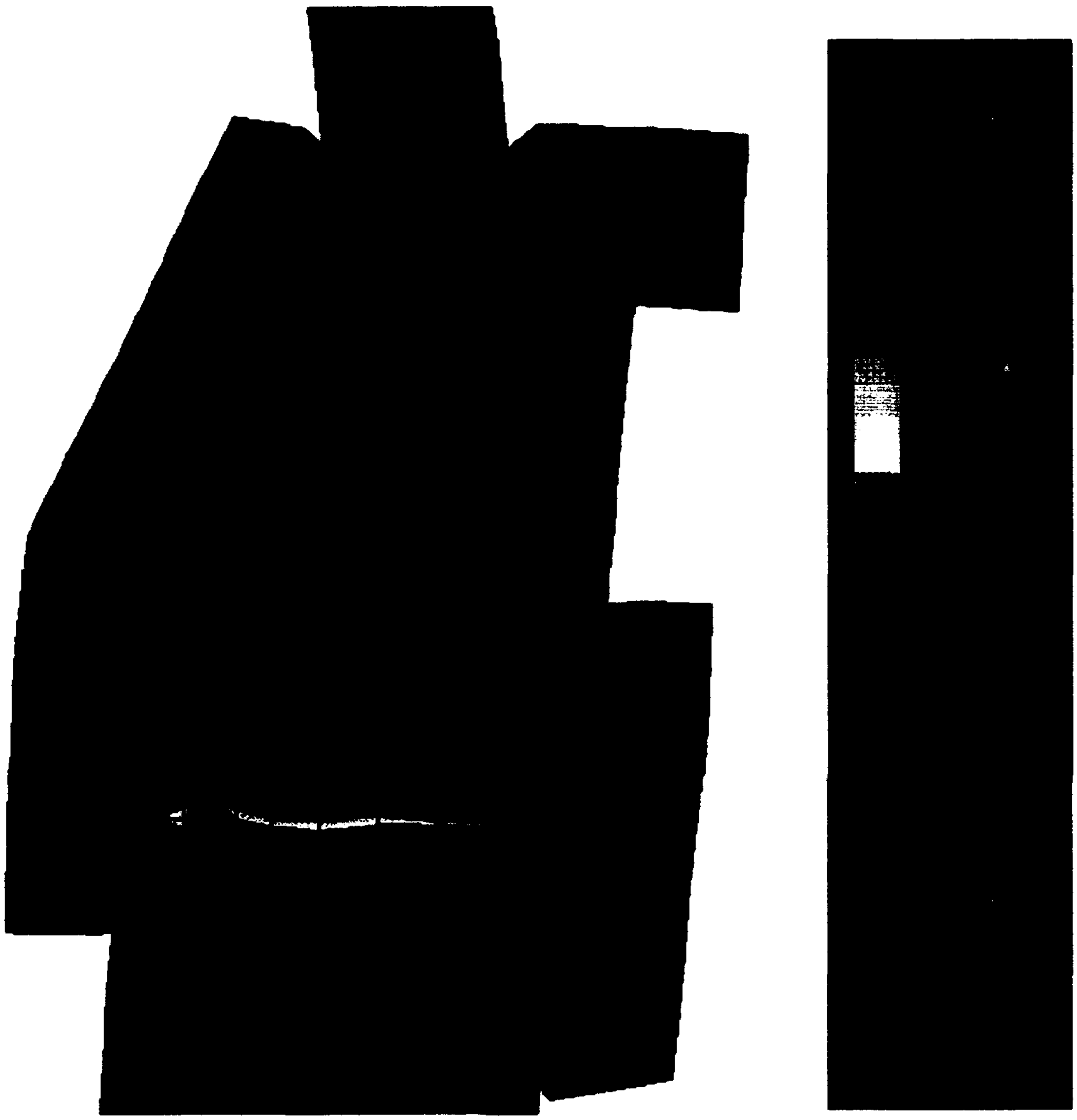


Figure 33. Typical fracture surface of a hemisphere that failed during pressure cycling.



20-inch validation pressure vessel: center support ring

Figure 34. Distribution of maximum principal stresses in a joint between cylinders encapsulated by Mod 0 end caps and supported by a removable metallic joint ring stiffener.



20-inch validation pressure vessel: hemi/cyl joint

Figure 35. Distribution of maximum principal stresses in a joint between a cylinder and hemisphere encapsulated by Mod 0 end caps.

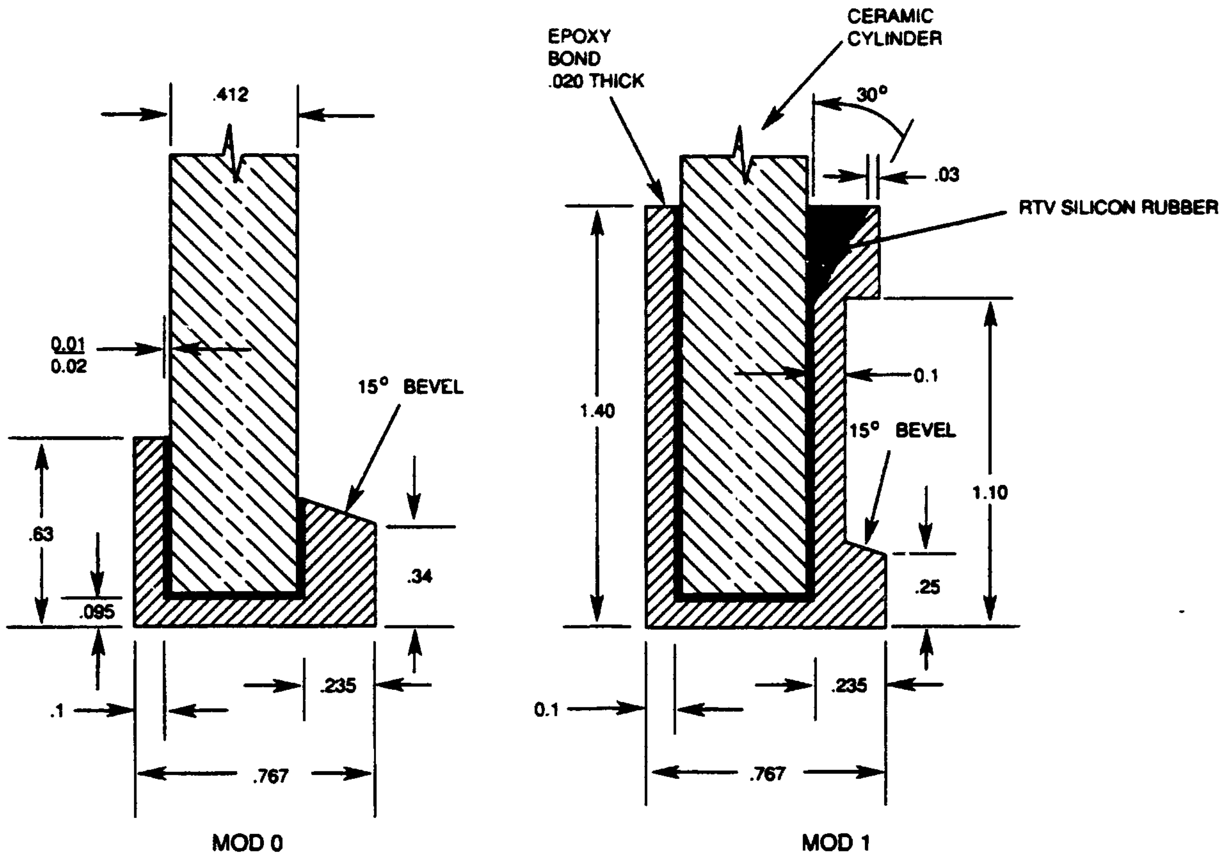


Figure 36. End caps for 12-inch-diameter ceramic cylinders. The Mod 1 end cap significantly reduces the formation of fatigue cracks on the plane-ceramic bearing surface.

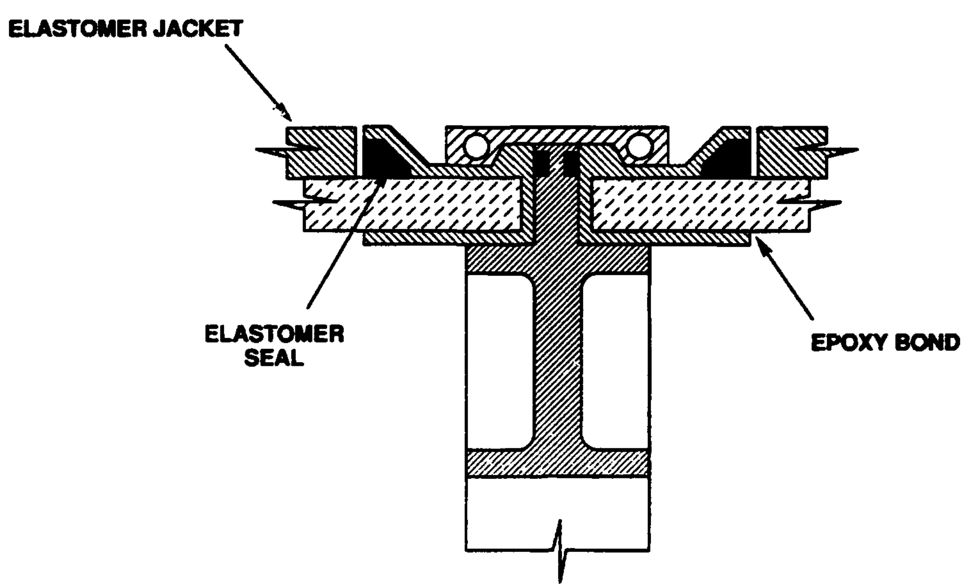


Figure 37. Optimized joint between ceramic cylinders incorporating the improved Mod 1 end caps.

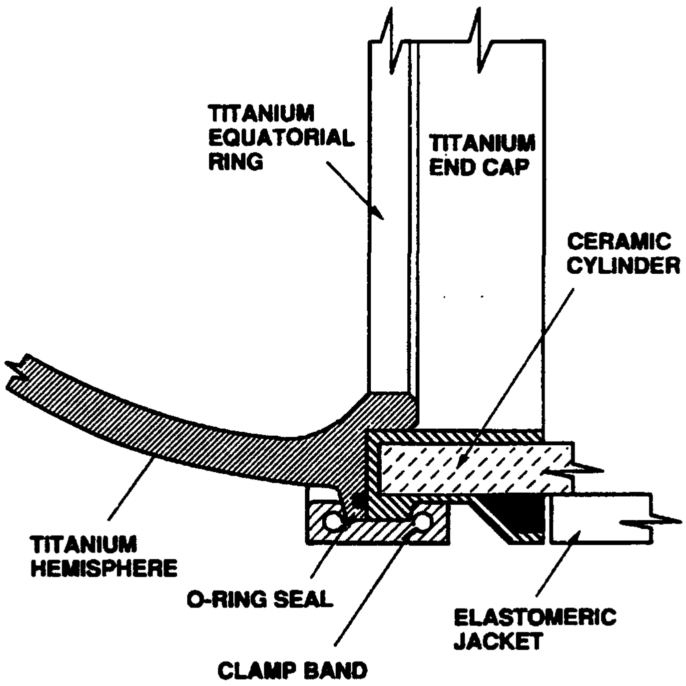


Figure 38. Optimized joint between ceramic cylinder and metallic bulkhead incorporating the improved Mod 1 end cap.

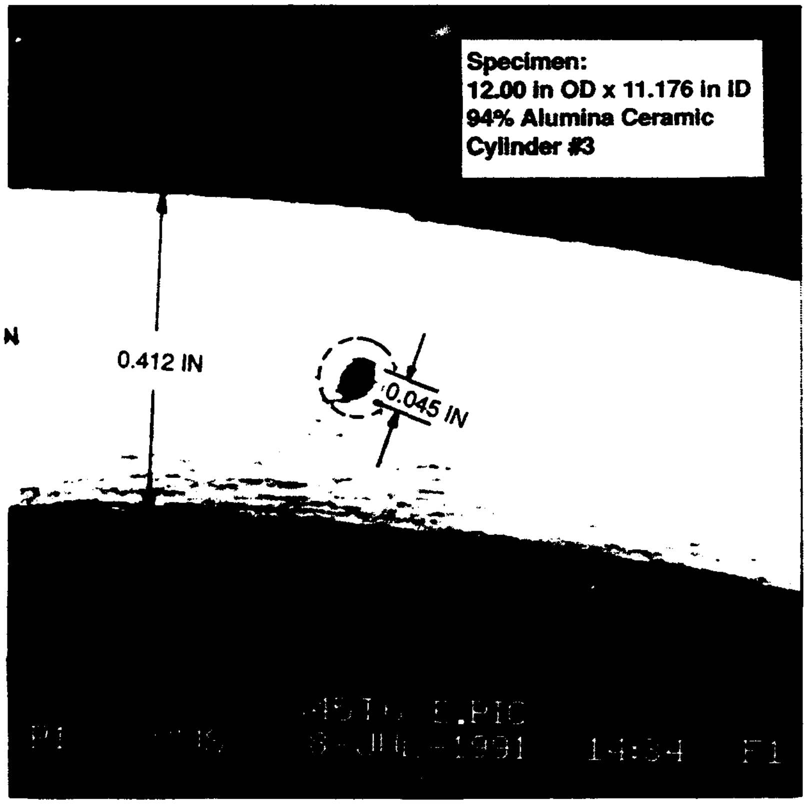


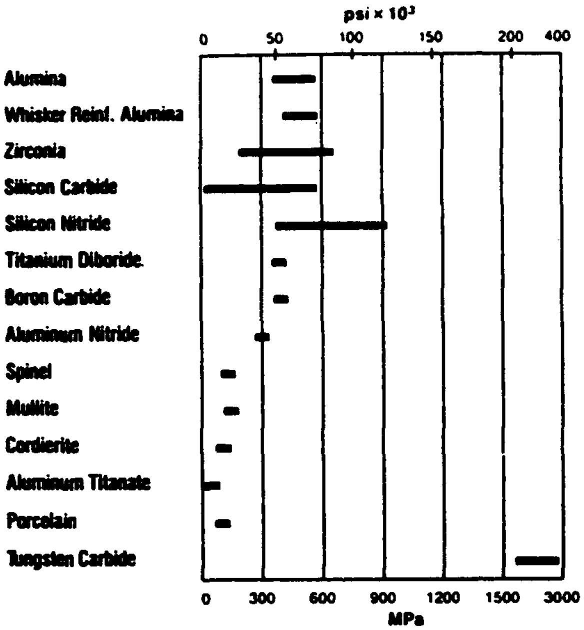
Figure 39. One of the large voids detected in the 12-inch-OD cylinder 3 by radiographic computed tomography.

Table 1. Premium structural materials used in construction of external pressure housings.

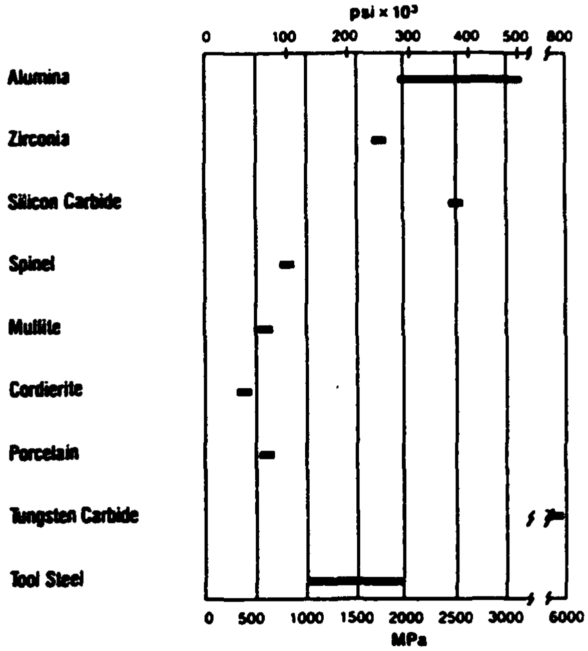
Material	Weight (lb/in^3)	Compressive Strength (kpsi)	$\frac{\text{Strength}}{\text{Weight}}$
Steel (HY80)	0.283	80	280
Steel (HY130)	0.283	130	460
Aluminum (7075-T6)	0.100	73	730
Titanium (6Al-4V)	0.160	125	780
Glass (Pyrex)	0.080	100	1250
Glass Composite	0.075	100	1330
Graphite Composite	0.057	100	1750
Beryllia Ceramic 96%	0.104	225	2160
Alumina Ceramic 94%	0.130	300	2310
Glass Ceramic (Pyroceram 9606)	0.093	350	3760
Silicon Carbide	0.114	450	3947
Boron Carbide	0.089	400	4494

Table 2. Physical properties of typical ceramic compositions for structural applications, sheet 1.

Flexural Strength
(@ 20°C MOR)



Compressive Strength
(@ 20°C)



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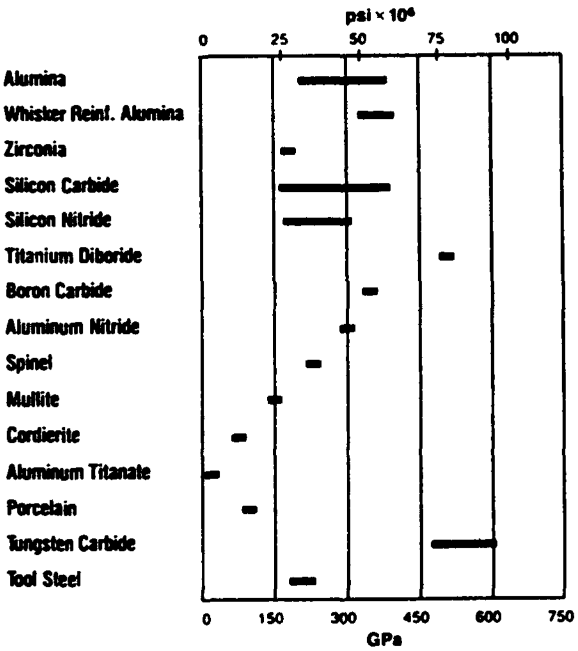
Elastic Modulus
(@ 20°C)



Stiffness to Weight Ratio Elastic Modulus/Density
(@ 20°C)

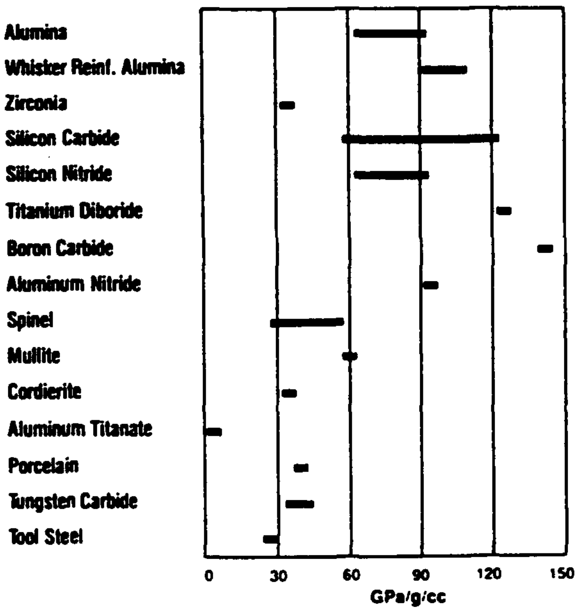
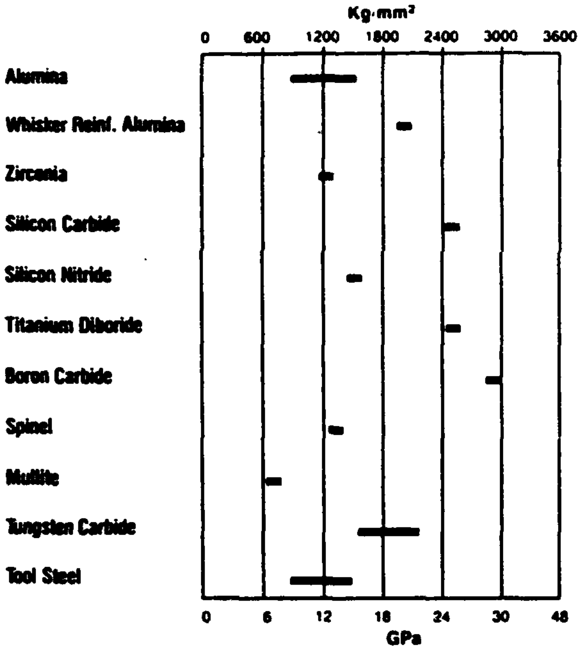
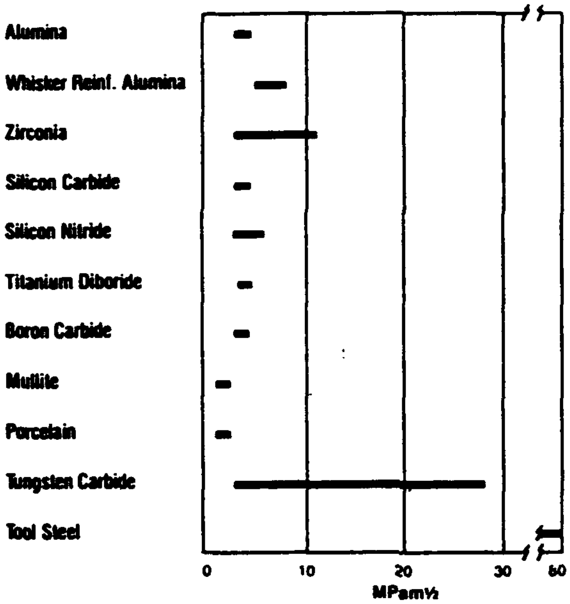


Table 2. Physical properties of typical ceramic compositions for structural applications, sheet 2.

Hardness
(500 gm load Vickers)



Fracture Toughness
(K_{Ic})



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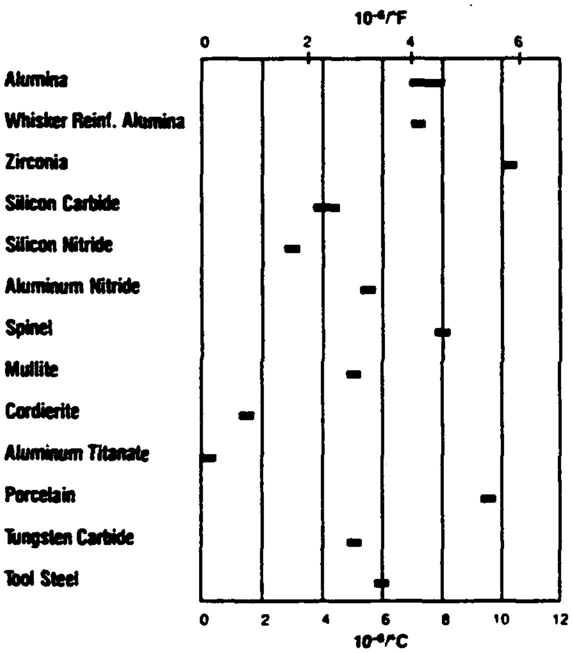
Coefficient of Thermal Expansion
(25-1000°C)



Thermal Conductivity
(@ 20°C)

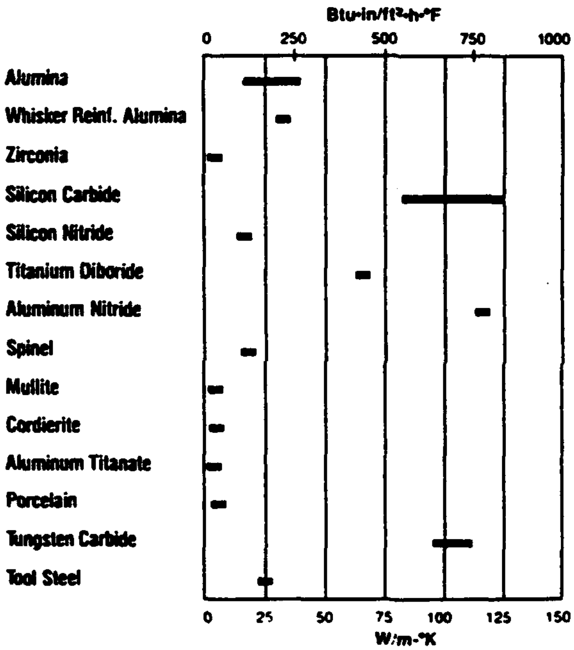
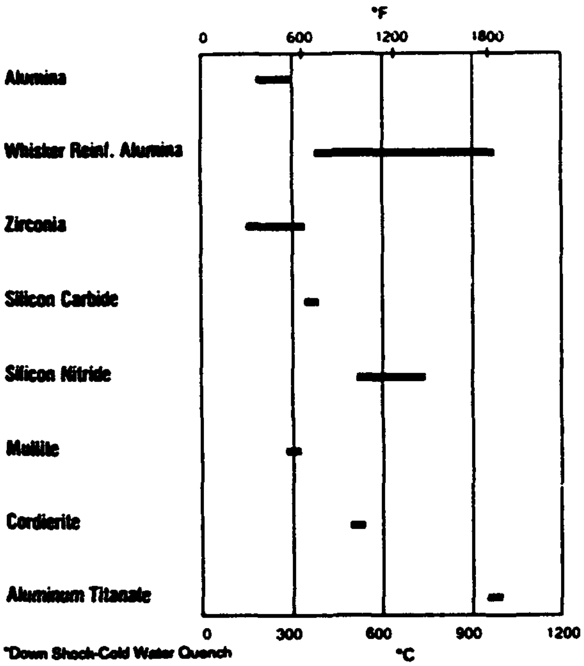


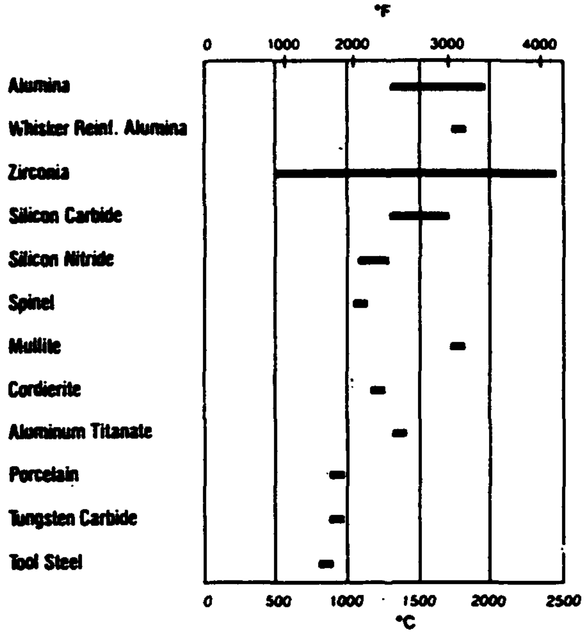
Table 2. Physical properties of typical ceramic compositions for structural applications, sheet 3.

Thermal Shock Resistance
(ΔTc)*



*Down Shock-Cold Water Quench

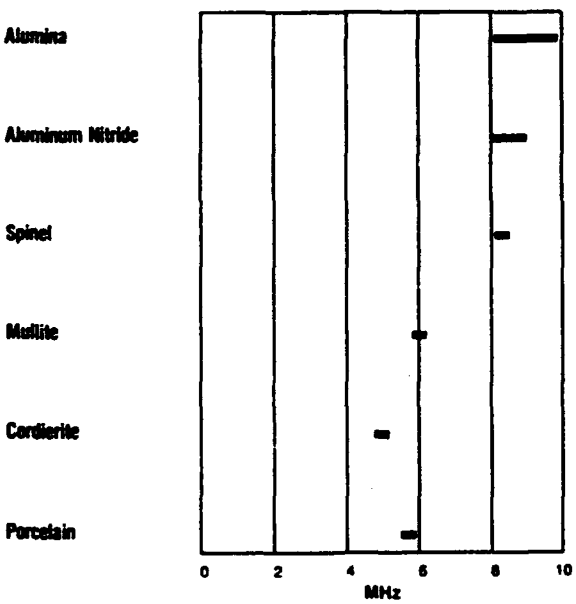
Maximum Use Temperature**



**No Load Conditions

(Coors Ceramics Bulletin #980)

Dielectric Constant
(@ 25°C 1 MHz)



Density

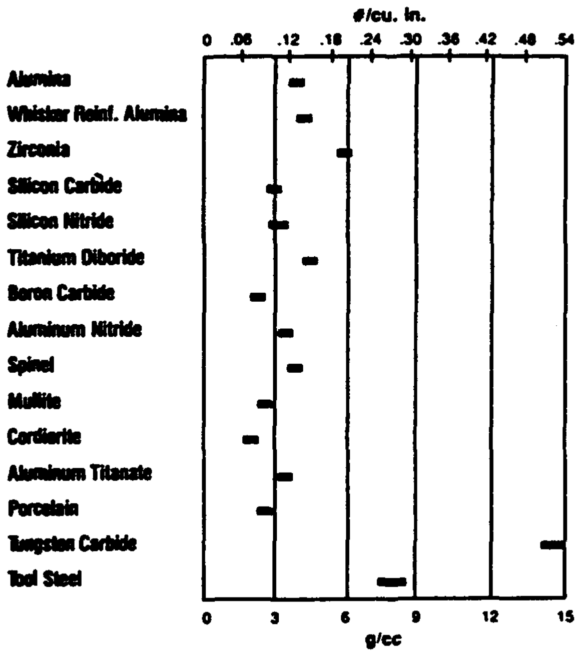


Table 3. Criteria useful in the selection of ceramic compositions to meet specific design requirements.

Criteria	Alumina Ceramics					SiC Whisker Reinforced	Beryllia		Carbides		Composites		Corning Glass 9606 Owens Illinois Cervit C-101
	85%	90%	94%	96%	99.5%		96%	99.5%	SiC	B_4C	Lanxide $SiC/Al_2O_3/AL$	Dow Chemical B_4C/AL	
Strength to Weight Ratio	Fair	High	High	High	Very High	Very High	High	Very High	Extra High	Extra High	High	Extra High	Very High
Stiffness to Weight Ratio	Fair	High	High	High	Very High	Very High	Very High	Extra High	Extra High	Extra High	High	Extra High	Low
State of Fabrication Technology	Mature	Mature	Mature	Mature	Mature	Youthful	Mature	Mature	Youthful	Youthful	Require Extensive Development	Require Extensive Development	Mature
Size Limitation	32 in. OD 30 in. L	32 in. OD 40 in. L	50 in. OD 30 in. L	32 in. OD 40 in. L	12 in. OD 24 in. L	12 in. OD 24 in. L	12 in. OD 24 in. L	12 in. OD 24 in. L	12 in. OD 24 in. L	12 in. OD 24 in. L	20 in. OD 30 in. L	6 in. OD 18 in. L	20 in. OD 30 in. L
Availability of Fabricators	2-3	2-3	2-3	2-3	2-3	2-3	1	1	2	1	1	1	2
Tooling Investment	Low	Low	Low	Low	Low	Low	Low	Low	Low	High	Medium	Medium	Very High
Cost of Fabrication per Part	Low	Low	Low	Low	Low	High	High	High	High	High	High	High	Very Low
Intrinsic Cost of Material	Low	Low	Low	Low	Low	High	Very High	Very High	High	Very High	High	Very High	Low
Heat Conductivity	Low	Low	Low	Fair	Fair	Fair	Very High	Very High	High	Fair	High	High	Very Low
Fracture Toughness	Low	Low	Low	Low	Low	Fair	Low	Low	Low	Low	Fair	Fair	Low

Table 4. Physical properties of alumina ceramic.

PROPERTIES*		UNITS	TEST	ALUMINA AD-85 Nom 85% Al_2O_3	AD-90 Nom 90% Al_2O_3	AD-94 Nom 94% Al_2O_3	AD-96 Nom 96% Al_2O_3	AD-99.5 Nom 99.5% Al_2O_3	AD-99.9% Nom 99.9% Al_2O_3
DENSITY		g/cc (#/cu in)	ASTM C20-83	3.41 (0.12)	3.60 (0.13)	3.70 (0.13)	3.72 (0.13)	3.89 (0.14)	3.96 (0.14)
SURFACE FINISH	AS-FIRED GROUND POLISHED	MICROMETRES (MICROINCHES) CLA	PROFILOMETER (0.75mm cutoff)	1.6 (63) 1.0 (39) 0.2 (8.0)	1.6 (63) 0.5 (20) 0.1 (3.9)	1.6 (63) 1.3 (51) 0.3 (12)	1.6 (63) 1.3 (51) 0.3 (12)	0.9 (35) 0.5 (20) 0.1 (3.9)	0.5 (20) 0.9 (35) < 0.03 (< 1)
CRYSTAL SIZE	RANGE AVERAGE	MICROMETRES (MICROINCHES)	THIN SECTION	2-12 (79-473) 6 (236)	2-10 (79-394) 4 (158)	2-25 (79-985) 12 (473)	2-20 (79-788) 11 (433)	5-50 (197-1970) 17 (670)	1-6 (39-236) 3 (118)
WATER ABSORPTION		%	ASTM C373-72	0	0	0	0	0	0
GAS PERM.		—	**	0	0	0	0	0	0
COLOR		—	—	WHITE	WHITE	WHITE	WHITE	IVORY	IVORY
FLEXURAL STRENGTH (MOR)	20°C	MPa (psi × 10^3)	ASTM F417-78	317 (46)	338 (49)	352 (51)	358 (52)	379 (55)	552 (80)
ELASTIC MODULUS SHEAR MODULUS BULK MODULUS TRANS. SONIC VEL. POISSON'S RATIO	20°C	GPa (psi × 10^6) GPa (psi × 10^6) GPa (psi × 10^6) m/sec (ft/sec) —	ASTM C848-78	221 (32) 96 (14) 138 (20) 8.2 (27) × 10^3 0.22	276 (40) 117 (17) 158 (23) 8.8 (29) × 10^3 0.22	296 (43) 117 (17) 165 (24) 8.9 (29) × 10^3 0.21	303 (44) 124 (18) 172 (25) 9.1 (30) × 10^3 0.21	372 (54) 152 (22) 228 (33) 9.8 (32) × 10^3 0.22	386 (56) 158 (23) 228 (33) 9.9 (32) × 10^3 0.22
STIFFNESS/WEIGHT	20°C	GPa/g/cc	—	65	77	80	81	96	97
COMPRESSIVE STRENGTH	20°C	MPa (kpsi)	ASTM C773-82	1930 (280)	2482 (360)	2103 (305)	2068 (300)	2620 (380)	3792 (550)
HARDNESS		GPa (kg/mm²)	—	9 (960)	10 (1058)	12 (1175)	11 (1088)	14 (1440)	15 (1551)
TENSILE STRENGTH	25 1000°C	MPa (kpsi)	ACMA TEST #4	155 (22) — (—)	221 (32) 103 (15)	193 (28) 103 (15)	193 (28) 96 (14)	262 (38) — (—)	310 (45) 221 (32)
FRACTURE TOUGHNESS	K_{Ic}	MPa·m$^{1/2}$	NOTCHED BEAM TEST	3-4	3-4	3-4	3-4	3-4	3-4
THERMAL CONDUCTIVITY	20°C	W/m·K (Btu·in/ft²·h·°F)	ASTM C408-82	16.0 (111)	16.7 (116)	22.4 (155)	24.7 (172)	35.6 (247)	38.9 (270)
COEFFICIENT OF THERMAL EXPANSION	25-1000°C	10^{-6}/°C (10^{-6}/°F)	ASTM C372-81	7.2 (4.0)	8.1 (4.5)	8.2 (4.6)	8.2 (4.6)	8.0 (4.6)	8.0 (4.5)
SPECIFIC HEAT	100°C	J/kg·K (cal/g·°C)	ASTM C351-82	920 (0.22)	920 (0.22)	880 (0.21)	880 (0.21)	880 (0.21)	880 (0.21)
THERMAL SHOCK RESISTANCE	ΔTc	°C (°F)	—	300 (570)	300 (570)	300 (570)	250 (480)	200 (392)	200 (392)
MAXIMUM USE TEMPERATURE		°C (°F)	No-load conds.	1400 (2552)	1500 (2732)	1700 (3092)	1700 (3092)	1750 (3182)	1900 (3452)
DIELECTRIC STRENGTH	6.35mm 3.18mm 1.27mm SPEC 0.64mm THICK 0.25mm	ac-kv/mm (ac-volts/mil)	ASTM-D116-76	9.4 (240) 13.4 (340) 17.3 (440) 21.6 (550) 28.3 (720)	9.2 (235) 12.6 (320) 17.7 (450) 22.8 (580) 29.9 (760)	8.7 (220) 11.8 (300) 16.7 (425) 21.6 (550) 28.3 (720)	8.3 (210) 10.8 (275) 14.6 (370) 17.7 (450) 22.8 (580)	8.7 (220) 11.4 (290) 16.9 (430) 22.8 (580) 33.1 (840)	9.4 (240) 12.8 (325) 18.1 (460) 23.2 (590) 31.5 (800)
DIELECTRIC CONSTANT	1 kHz 1 MHz 1 GHz	25°C	ASTM D150-81 ASTM D2520-81	8.2 8.2 8.2	8.8 8.8 8.8	9.1 9.1 9.1	9.0 9.0 9.0	9.8 9.7 9.7	9.9 9.8 —
DISSIPATION FACTOR	1 kHz 1 MHz 1 GHz	25°C	ASTM D150-81 ASTM D2520-81	0.0014 0.0009 0.0014	0.0006 0.0004 0.0007	0.0007 0.0004 0.0010	0.0011 0.0001 0.0002	0.0002 0.0003 0.0002	0.0020 0.0002 —
LOSS INDEX	1 kHz 1 MHz 1 GHz	25°C	ASTM D150-81 ASTM D2520-81	0.011 0.007 0.010	0.005 0.004 0.005	0.007 0.004 0.009	0.010 0.001 0.002	0.002 0.003 0.002	0.020 0.002 —
VOLUME RESISTIVITY	25°C 300°C 500°C 700°C 1000°C	ohm-cm²/cm	ASTM D1829-66	>10^{14} 4.6 × 10^{10} 4.0 × 10^8 7.0 × 10^6 —	>10^{14} 1.4 × 10^{11} 2.8 × 10^8 7.0 × 10^6 8.6 × 10^5	>10^{14} 1.2 × 10^{11} 4.8 × 10^8 2.1 × 10^7 5.0 × 10^5	>10^{14} 3.1 × 10^{11} 4.0 × 10^9 1.0 × 10^8 1.0 × 10^6	>10^{14} — — — —	>10^{14} >10^{14} 3.3 × 10^{12} 9.0 × 10^9 1.1 × 10^7
Te VALUE		°C (°F)	TEMP AT WHICH RESISTIVITY IS 1 MEGOHM-CM	850 (1562)	960 (1760)	950 (1742)	1000 (1832)	—	1170 (2138)
CORROSION RESISTANCE	WEIGHT LOSS	mg/cm²/day	95% H_2SO_4 @20°C–NOTE 3 95% H_2SO_4 @100°C–NOTE 3	0.04 1.0	0.03 0.5	— —	— —	0.01 0.1	0.01 0.1
IMPINGEMENT		—	NOTE 4	1.00	0.45	0.52	0.63	0.47	0.14
RUBBING		—	NOTE 4	1.00	0.36	—	0.75	—	0.55

(COORS CERAMICS BULLETIN #980)

Table 5. Comparison of alumina ceramic to titanium alloy.

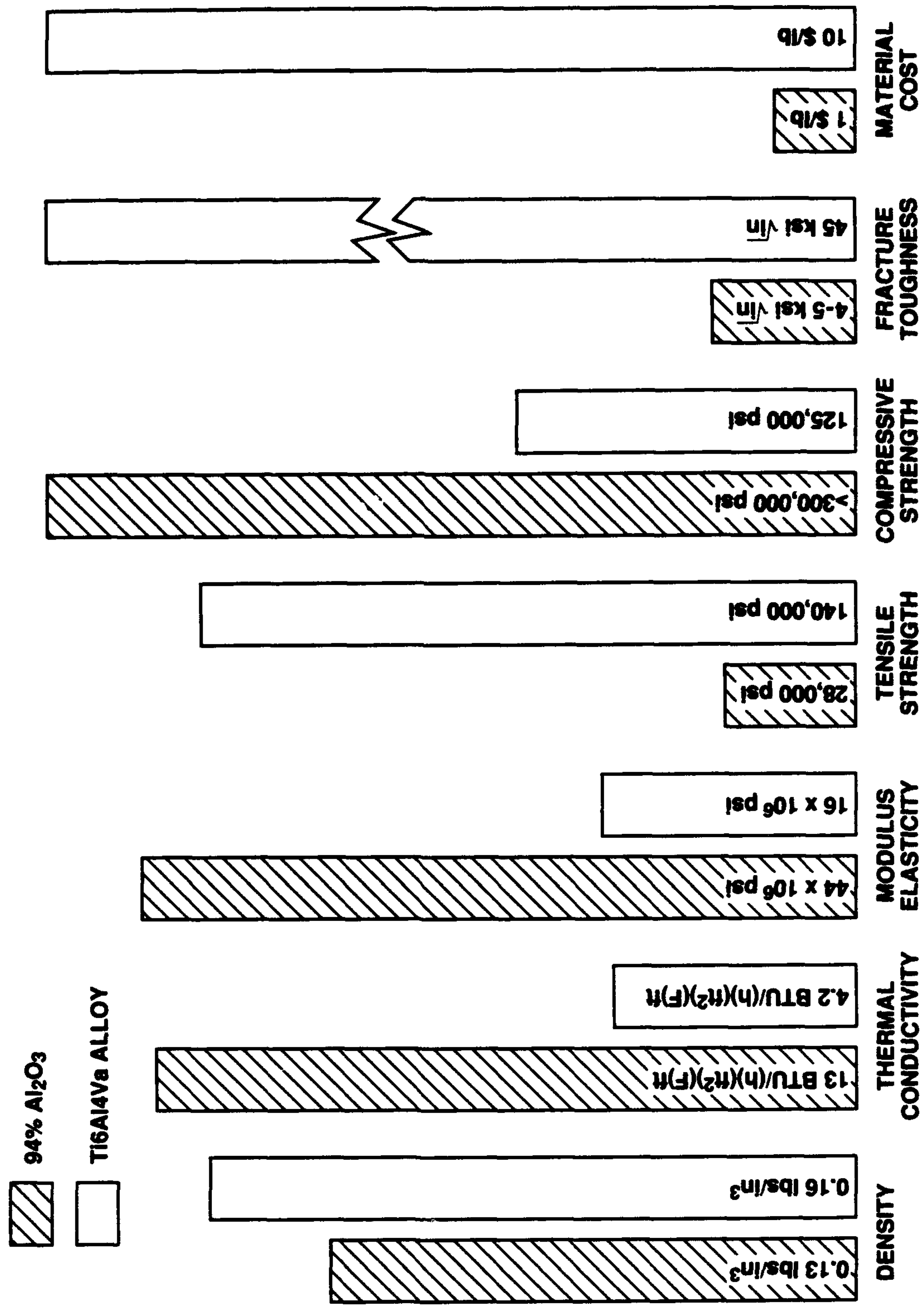


Table 6. Dimensions of components used in the assembly of pressure housings.

6 inch Diameter Housings

Model 1	Cylinders - 99.5 percent Al_2O_3 composition 6.0 inch OD x 9.0 inch L x 0.188 inch thick
Model 2	Cylinders - 94 percent Al_2O_3 composition 6.038 inch OD x 9.0 inch L x 0.206 inch thick
Model 3	Cylinders - 94 percent Al_2O_3 composition 6.038 inch OD x 18.25 inch L x 0.206 inch thick

12 inch Diameter Housings

Type 1	Cylinders - 94 percent Al_2O_3 composition 12 inch OD x 18 inch L x 0.412 inch thick
Mod 1	Hemisphere - 94 percent Al_2O_3 composition Single 2 inch penetration at center of hemisphere 11.79 inch OD, thickness constant at 0.2 inch except for a penetration flange of 0.5 inch thickness.
Mod 2	Hemisphere - 94 percent of Al_2O_3 composition Single 2 inch penetration at center of hemisphere 11.79 inch OD, thickness increases uniformly from 0.2 inch at equator to 0.4 inch at center.
Mod 3	Hemisphere - 94 percent Al_2O_3 composition Single 2 inch penetration at center of hemisphere 11.79 inch OD, thickness constant at 0.2 inch thickness.
Mod 4	Hemisphere - 94 percent Al_2O_3 composition Four 2 inch penetrations equally spaced at 45° latitude 11.79 inch OD, thickness constant at 0.02 inch, except for a reinforcement band of 0.4 inch thickness around penetrations.
Mod 5	Hemisphere - 94 percent Al_2O_3 composition Four 2 inch penetrations equally spaced at 45° latitude, and a single 3 inch penetration at the center of hemisphere 11.79 inch OD, thickness increases uniformly from 0.2 inch at equator to 0.4 inch at center.

Table 7. Physical properties of expoxy adhesive used for bonding end caps to ceramic cylinders and hemispheres.

Castings	**Parts by weight**
Araldite GY 6010	100
Hardener XU HY 283	70
(Supplied by Ciba-Geigy)	
Preparation	
Resin and hardener were degassed separately and mixed thoroughly by hand. The mixture was then degassed to eliminate air bubbles.	
Cure schedule (18-in casting)	7 days at 23°C
Tensile Properties	
(at 23°C unless otherwise noted)	
Tensile strength (psi)	4,700
Yield elongation (%)	3.6
Break elongation (%)	26.1
Tensile Modulus (psi)	
at 23°C	272,500
at 0°C	300,300
at -20°C	314,100
at -40°C	323,400
at -100°C	355,700
Compressive Properties	
Compressive strength (psi)	13,400
Compressive modulus (psi)	328,000
Yield compression (%)	5.3
Ultimate compression (psi)	34,200
Ultimate compression (%)	53.7
Flexural Properties	
Flexural strength (psi)	7,100
Flexural modulus (psi)	154,000
Lap shear* (psi)	3,700
HDT (°C)	37

* Alclad 2024 T-3 Aluminum Alloy 1/2-in x 1-in lap joint in shear at room temperature.

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13. ABSTRACT *(Maximum 200 words)*

A test program has been conducted to develop design concepts for assembling large external pressure housings from ceramic cylinders and hemispheres by joining them with removable titanium joint rings and split wedge bands. The proposed design concepts have been validated with 6- and 12-inch-diameter housings assembled from many interchangeable housings components.

The test results show that there appears to be no reduction in structural performance under external pressure associated with (1) linear scaling up of ceramic housing components, and (2) the presence of inclusions <0.05 inch in diameter. Weight-to-displacement of 0.6 has been achieved by housings assembled from 94-percent alumina monocoque cylinders and hemispheres designed not to exceed −150,000 psi compressive stress. The cyclic fatigue life of the ceramic components is determined by the rate of crack growth on the ceramic bearing surfaces under axial bearing loading. The rate of crack growth is minimized by encapsulating the ends of ceramic components in titanium end rings filled with epoxy adhesive.

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Dr. Stachiw is the author of over 100 technical reports, articles, and papers on design and fabrication of pressure resistant viewports of acrylic plastic, glass, germanium, and zinc sulphide, as well as pressure housings made of wood, concrete, glass, acrylic plastic, and ceramics. His book on "Acrylic Plastic Viewports" is the standard reference on that subject.

For the contributions to the Navy's ocean engineering programs, the Navy honored him with the Military Oceanographer Award and the NCCOSC's RDT&E Division honored him with the Lauritsen-Bennett Award. The American Society of Mechanical Engineers recognized his contributions to the engineering profession by election to the grade of Life-Fellow, as well as the presentation of Centennial Medal, Dedicated Service Award and Pressure Technology Codes Outstanding Performance Certificate.

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